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Impact of ITCZ width on global climate: ITCZ-MIP

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Abstract. The width of the ITCZ affects tropical rainfall, Earth's albedo, large-scale circulation and climate sensitivity; yet we do not understand what controls it. To better understand the ITCZ width and its effects on global climate, we present a protocol to force changes in ITCZ width in climate models. Starting from an aquaplanet configuration with a slab ocean, adding surface heat fluxes in the deep tropics forces the ITCZ to narrow, and subtracting them causes it to widen. The protocol successfully generates changes in ITCZ width in four climate models; within each model, ITCZ width responds linearly to forcing magnitude and sign. Comparing across the four climate models, a response to varying ITCZ width that is remarkably consistent among models is the ITCZ strength, which is greater the narrower the ITCZ. On the other hand, the effect of varying ITCZ width on climate sensitivity is divergent among our four models, varying even in sign. These results indicate that idealized model experiments have the potential to increase our understanding of ITCZ width.

1 Introduction

The Inter-Tropical Convergence Zone (ITCZ) has some of the strongest and most consistent convection and precipitation on the planet. It plays an important role driving the energy and mass fluxes of global atmospheric circulation and is strongly coupled to the Hadley cell – by some definitions, coinciding with its ascending branch. Deep convection in the core of the ITCZ drives teleconnections via Rossby wave trains that propagate to the midlatitudes of the Northern and Southern Hemispheres, thus potentially affecting many aspects of global climate, including the width of the tropics and the location of the storm tracks (Watt-Meyer and Frierson, 2019).

The width of the ITCZ and its changes may also influence the response to global warming beyond the deep tropics, potentially influencing global precipitation (Su et al., 2017) and climate sensitivity (Barsugli et al., 2005; Tian, 2015; Webb and Lock, 2020). There are indications that the width of the ITCZ may decrease in response to global warming; in climate model projections forced by increasing greenhouse gases, the ITCZ narrows (Byrne and Schneider, 2016a; Byrne et al., 2018), and observational analysis has revealed evidence of decreasing ITCZ width in some ocean basins (Wodzicki and Rapp, 2016).

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Fundamental understanding of the changes in ITCZ width and its effects on global climate is therefore important. However, until recently there has been relatively little research on it, other than the double ITCZ bias in climate models, which we set aside for this study (reasoning for which is discussed in Section 2.2.1). Existing literature on what controls the width of the ITCZ, including energetic and potential dynamical theories, was synthesized by Byrne et al. (2018). Additional explanations for the ITCZ width and its variations have since been put forward, including aggregation associated with zonal asymmetries (Popp and Bony, 2019), cloud radiative effects (Harrop and Hartmann, 2016; Dixit et al., 2018), Ekman balance in the tropical boundary layer (Byrne and Thomas, 2019), and variability in the seasonal cycle of ITCZ location (Donohoe et al., 2019). Most of these studies focused on experiments using a single climate model.

Despite that current comprehensive climate models share many similarities, comparing simulations from different models can be useful, especially when they reveal different yet plausible emergent behaviors. Of particular relevance to the ITCZ, tropical clouds and precipitation have dramatically different responses to increasing greenhouse gases in different climate models, even in simulations with an aquaplanet configuration, which is an idealized configuration with no continents or seasonal cycle (Stevens and Bony, 2013). Developing understanding of ITCZ width that is robust across climate models thus calls for a Model Intercomparison Project (MIP).

In response to this calling, and in order to investigate the effects of ITCZ width on global climate, we introduce ITCZ-MIP. The experimental protocol, described in the next section, is based around simulations run in aquaplanet slab-ocean configurations, in which the ITCZ is forced to change via additional heat fluxes applied at the surface. A pilot set of 4 models (three standard CMIP-class models and one with no cloud radiative effects) serves to demonstrate and validate the protocol. Two unanticipated behaviors emerge in the pilot MIP: a relationship between ITCZ width and global-mean temperature (in the absence of external forcing), and a remarkably consistent relationship between ITCZ width and strength (Section 3). The pilot simulations enable an exploratory analysis of two specific questions about how ITCZ width affects global climate (Section 4): What mechanisms connect the ITCZ width to the width of the Hadley cell and the location of the storm tracks? And, does equilibrium climate sensitivity depend on the ITCZ width? Finally, we reflect on key learnings thus far and new questions prompted by the pilot MIP.

2 ITCZ-MIP Experimental Protocol Description

In this section we present the experimental protocol: the approach to generate changes in the width of the ITCZ. Then we document the metrics we use to quantify ITCZ width and describe the model simulations in the pilot MIP.

2.1 Aquaplanet configuration

Aquaplanet configurations are at an intermediate level in the model hierarchy. They exclude geography, and thus zonal asymmetry, as well as the seasonal cycle of solar radiation. Otherwise, they can have full atmospheric dynamics and physics, including radiative transfer, and parameterized clouds and precipitation. For surface boundary conditions, they can have prescribed SSTs

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or a slab ocean component, which represent ocean dynamics only indirectly by prescribing heat fluxes in each ocean grid – but still representing the thermal inertia of the ocean and also surface fluxes of water and heat.

Despite their simplifications, when different climate models are run in aquaplanet configuration, they can still have dramatically different behavior - especially in terms of clouds, precipitation, and their responses to greenhouse gas forcing (Stevens and Bony, 2013). The differences among aquaplanet simulations often contain the relevant mechanisms to their parent Earth-configuration models climate and sensitivity to warming (Medeiros et al., 2008, 2015; Ringer et al., 2014).

The ITCZ-MIP experimental protocol focuses around a series of aquaplanet simulations coupled to a slab ocean. Simulations follow the Aqua-Planet Experiment (APE)-protocol of Neale and Hoskins (2000) and Williamson et al. (2012). Each simulation has perpetual equinoctial solar insolation, solar constant equal to 1365 W m^{-2}, a diurnal cycle, CO_2 concentrations of 348 (or 1392 ppm for quadrupled CO_2), zonally symmetric latitude-height ozone (as in Williamson et al., 2012). Most simulations have a slab ocean with a 10-m mixed layer depth. A full radiation scheme is recommended in which the CO_2 concentration can be directly specified; an alternative for gray radiation schemes is to implement an equivalent CO_2 concentration as in TRAC-MIP (Voigt et al., 2016).

2.2 Control experiments

One control simulation with a prescribed SST profile is necessary in order to run the slab ocean. Two slab-ocean control simulations are then run, one for each CO_2 concentration.

2.2.1 A single ITCZ

The double ITCZ bias which is common to most climate models currently and has persisted for decades over generations of climate models. Recent mechanisms put forward that may be responsible for this bias are atmosphere-ocean feedbacks and biased strength of regional patterns of seasonal convection (e.g., Song and Zhang, 2019; Song et al., 2019).

The double-ITCZ bias in climate models is an interesting problem in its own right, and it might be in some sense related to the width of the ITCZ in full present-day geography settings. However, there may be insight to gain about ITCZ width from a more idealized, simplified level of the hierarchy of models and configurations. Therefore, we choose to focus on experimental configurations that result, for the most part, in just one zonal-mean precipitation maximum in the tropics. We accomplish this by starting from an initial prescribed SST profile that generates a single ITCZ.

The prescribed-SST control simulation (itcz-SST in Table 1) is generated with the APE-protocol's Control prescribed-SST profile (Neale and Hoskins, 2000). The Control SST profile is described by Equation 1,

$$\mathrm{SST}(\phi) = \begin{cases} 27\left(1-\sin^2\left(\frac{3\phi}{2}\right)\right)\,^\circ C, & \text{if } -\frac{\pi}{3} < \phi < \frac{\pi}{3}, \\ 0^\circ C, & \text{otherwise.} \end{cases} \tag{1}$$

The Control SST profile differs from the default "Qobs" profile used in e.g., the CFMIP CMIP6 simulations (Webb et al., 2017) in that the Control SST profile has a narrower peak. This narrower peak in SST also results in narrower ITCZ (Rajendran et al., 2013), and avoids a split ITCZ in the control state.

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2.2.2 Slab ocean and prescribed surface heat fluxes

Interactions between the ocean and atmosphere are fundamental to the climate, particularly in the tropics. But fully coupled ocean-atmosphere simulations are expensive and a step towards the comprehensive end of the model hierarchy. We choose to focus ITCZ-MIP on a middle ground: the slab ocean (also known as mixed-layer ocean, e.g., Stouffer and Manabe, 1999), in which each grid cell has prognostic sea surface temperature, a fixed heat capacity, and prescribed surface heat fluxes - called q-fluxes - to represent convergence of ocean heat transport that would be driven by ocean currents.

The process for running the slab ocean simulations in this protocol builds on the prescribed-SST control simulations. Output from the itcz-SST control simulation is used to calculate the climatological surface energy imbalance (F), from which q-fluxes are generated to run all slab-ocean experiments, i.e., Experiments 1-8 in Table 1. The surface imbalance is the sum of radiative and turbulent heat fluxes,

$$F = SW + LW - LH - SH - SN, \tag{2}$$

where $SW = SW_{\downarrow} - SW_{\uparrow}$ is the net shortwave radiative flux at the surface, $LW = LW_{\downarrow} - LW_{\uparrow}$ is the net surface longwave radiative flux, LH is the latent heat flux associated with evaporation, SH the sensible heat flux and SN the latent heat flux associated with frozen precipitation. The up and down arrows correspond to upward and downward fluxes, respectively. Positive values of F indicate excess downward energy at the surface (i.e., the surface temperatures would be warmer than the specified SST if they were allowed to vary). If LH and SN are not directly output by a climate model, they can instead be calculated using the surface evaporation and frozen precipitation using the appropriate latent heat of evaporation and latent heat of fusion. The global mean F does not explicitly need to equal zero, but F should be very similar to the global mean net TOA radiative flux in order for the atmosphere to stay close to energetic balance (this is also true for the specified-SST simulation). The present-day CO_2 slab-ocean control simulation itcz-slab (Experiment 1) and increased CO_2 control itcz-slab-4xCO2 (Experiment 6) need only this base-state q-flux forcing F to run.

2.3 Q-flux forcing to change ITCZ width

Experiments where ITCZ width varies within one climate model at a time distill the essence of the ITCZ width variation and its effects on global climate. Next, we come to the heart of the ITCZ-MIP protocol: applying additional q-fluxes to generate variations in ITCZ width. The additional q-flux (q_{itcz}) has the shape of the top half of a sinusoid in latitude, reaching a maximum at the equator, with compensating heat flux of the opposite sign poleward of the subtropics to balance the added flux in the global mean.

$$q_{itcz}(\phi) = \begin{cases} A\cos\left(\frac{\pi}{2}\frac{\phi}{\Delta\phi}\right), & |\phi| < \Delta\phi \\ 0 & \Delta\phi < |\phi| < 2\Delta\phi \\ B, & |\phi| > 2\Delta\phi, \end{cases} \tag{3}$$

where A is the magnitude of heating at the equatorial peak, and $\Delta\phi$ is the width of the anomalous heating at the equator ($\Delta\phi = 5°$). The compensation applied evenly poleward of the subtropics determined by the term B is given by (4) and is

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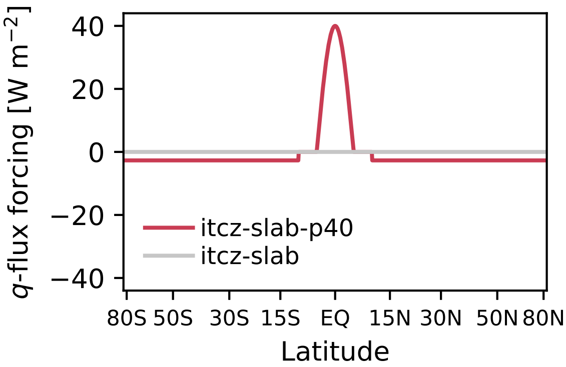

Figure 1. The q-flux with $A = 40$ W m^{-2}, described by (3).

computed with the condition that the global-mean q_{itcz} is zero. This is achieved by setting $\int_{-\pi/2}^{\pi/2} q_{itcz}(\phi)\cos(\phi)\,d\phi = 0$. Specifically,

$$B = \frac{A\cos(\Delta\phi)}{2\left(1-\sin\left(2\Delta\phi\right)\right)\left(\frac{\Delta\phi}{\pi} - \frac{\pi}{4\Delta\phi}\right)}. \tag{4}$$

The total q-flux (q) for each experiment is,

$$q = -F + q_{itcz}, \tag{5}$$

where a positive q represents a flux of energy from the ocean to the atmosphere (i.e. upward); F is given by (2) and q_{itcz} is given by (3). We note that when $A = 0$ in (3), the total q-flux is given by $q = -F$. The q_{itcz} with $A = 40$ W m^{-2} for the itcz-slab-p40 experiment is shown in Fig. 1.

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2.4 Experiment collection

In order to test the linearity of variations in ITCZ width and climate responses to forcing, two positive and negative A values are applied in separate experiments: $A = -40, -20, 20, 40$ W m^{-2}. An analogous set of quadrupled carbon dioxide simulations enables examination of the effect of base-climate ITCZ width on global warming.

The experiments that constitute ITCZ-MIP are listed in Table 1. They are broken down into two tiers, analogous to the CMIP protocol. The Tier I experiments are requested from all contributing models, and Tier II are highly encouraged (but not essential for contributing models to ITCZ-MIP). Each experiment includes 30 years of simulations after removing a suitable period to allow for spin up (the spin up will vary between models, and may be up to five years).

The variables requested as part of ITCZ-MIP are listed in Table 2. The procedure for ITCZ-MIP is summarized as follows:

1. Generate the control experiment (itcz-SST) using the SST profile in (1).

2. Compute the q-flux (q_{itcz}) and climatological zonal-mean surface energy imbalance (F) from the itcz-SST run using (2–5) for the neutral ITCZ width ($A = 0$).

3. Impose the total q-flux (q) from (5) in the slab ocean experiment to generate itcz-slab. Other than these changes to a slab-ocean boundary condition, the same parameters and settings should be used as in itcz-SST.

4. Repeat step 3 for two positive deep tropical q-flux forcing corresponding to a narrower ITCZ ($A = 20, 40$ W m^{-2}) and two negative forcing (wider ITCZ, $A = -20, -40$ W m^{-2}) setups.

5. Repeat step 4 using quadrupled CO_2 concentration (1392 ppm).

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Table 1. ITCZ-MIP experiments. Tier I experiments are essential and Tier II experiments are highly encouraged. The scaling factor A is used in (3) to set the ITCZ width.

No.	Experiment name	Description	A [W m^{-2}]	CO_2 [ppm]
Tier I experiments				
0	itcz-SST	SST profile using (1)	N/A	348
1	itcz-slab	Slab ocean control	0	348
2	itcz-slab-m20	As in 1 and a wider ITCZ	-20	348
3	itcz-slab-p20	As in 1 and a narrower ITCZ	+20	348
Tier II experiments				
4	itcz-slab-m40	As in 2 and a wider ITCZ	-40	348
5	itcz-slab-p40	As in 3 and a narrower ITCZ	+40	348
6	itcz-slab-4xCO2	As in 1 and $4\times CO_2$	0	1392
8	itcz-slab-4xCO2-m20	As in 2 and $4\times CO_2$	-20	1392
9	itcz-slab-4xCO2-p20	As in 3 and $4\times CO_2$	+20	1392
7	itcz-slab-4xCO2-m40	As in 4 and $4\times CO_2$	-40	1392
8	itcz-slab-4xCO2-p40	As in 5 and $4\times CO_2$	+40	1392

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Table 2. Model output variables and frequency requested for all of the experiments listed in Table 1. The variable names listed are standard CMIP variable names. All output should follow CMIP6 standards, i.e. in terms of dimensional names and units.

	Variable name	Description
Tier I; Monthly 3D	ua, va, wap, ta, hur, hus, zg	winds, air temperature, relative humidity, specific humidity and geopotential height
Tier I; Monthly 2D	uas, vas, tauu, tauv	surface winds and wind stresses
	tas, huss	near-surface temperature and specific humidity
	pr, prc, prsn	precipitation, convective precipitation, snow
	ts, ps	SST, surface pressure
	prw, clt, evspsbl	liquid water path, cloud fraction, evaporation
	hfls, hfss	Sensible and latent heat flux
	rlds, rlus, rsds, rsus, rsdt, rsut, rlut	All-sky radiative fluxes
	rldscs, rluscs, rsdscs, rsuscs, rsutcs, rlutcs	Clear-sky radiative fluxes
	q-flux	The imposed q-flux from (5)
Tier I; Daily 2D	pr, prc, evspsbl, clt, tas, huss, wap500	As above but for daily data
Tier II; Monthly 3D	usvs, vsts, vsqs	Eddy fluxes of momentum, heat, moisture
Tier II;Daily 3D	ua, va, ta, hus, zg, wap	As above but for daily data

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2.5 Pilot ITCZ-MIP models

We run the ITCZ-MIP protocol with four models to demonstrate that the experimental approach does indeed result in varying ITCZ width in a handful of different models, and to highlight a few interesting aspects of the climate responses and motivate contributions with more models. The goal of this pilot study is to lay a framework that increases the likelihood of success for a full-scale MIP.

The pilot MIP models include three from the CMIP-class, and one with some idealizations. CESM2.0 simulations (which have the CAM6 atmosphere component, Danabasoglu et al., 2020) use the finite volume grid at nominal 1 degree resolution. Two sets of simulations have a nominal 2-degree resolution: CESM1.2 (CAM5 atmosphere, Neale et al., 2012; Meehl et al., 2013) and GFDL-AM2.1 (Delworth et al., 2006).

The fourth model in the pilot MIP, Isca, is a step on the hierarchy towards idealized and away from comprehensive. The Isca climate modeling framework is a variant of the GFDL Flexible Modeling System (FMS) configured with additional parameterizations, new python interfacing (replacing the bash scripted run scripts) and test suites for Earth and other planets (Vallis, G. K. et al., 2018). Isca simulations are run at T42 ($2.8^\circ \times 2.8^\circ$) resolution with 41 vertical levels (0.027 hPa top). They use the SOCRATES radiation scheme and all other parameterizations as standard for the GFDL FMS: simple Betts-Miller convection, no clouds, and simple boundary layer scheme.

2.6 ITCZ width metric

In order to examine variations in ITCZ width quantitatively, it is necessary to choose a metric. In the aquaplanet configuration, with no zonal-mean asymmetry or seasonal cycle and just one maximum of zonal-mean precipitation in the tropics (by design, see Section 2.2.1) in most simulations, this is relatively straightforward. Nonetheless, there are multiple ways to quantify ITCZ width, some of which are described in Byrne et al. (2018). These include a mass-based definition, which is the meridional distance between extrema of the streamfunction that bound the region of mean ascending flow, and a moisture-based definition, which is the meridional distance between zero-crossings of tropical precipitation minus evaporation. We focus on the "mass" ITCZ width; the distance between latitudes closest to the equator with a zero-crossing of the meridional derivative of the 500 hPa streamfunction. In this manuscript, we express the distance in degrees latitude.

3 Results: Validating the protocol

In this section we demonstrate successful implementation of the protocol in multiple modeling frameworks, and then explore potential limitations of the experiments.

3.1 ITCZ width variations driven by prescribed q-fluxes

First, we verify that the prescribed q-fluxes result in changes in ITCZ width. Figure 2 shows the total zonal-mean precipitation for each of the q-flux forcings, as well as their differences from the itcz-slab control experiment for one model (CESM2). The

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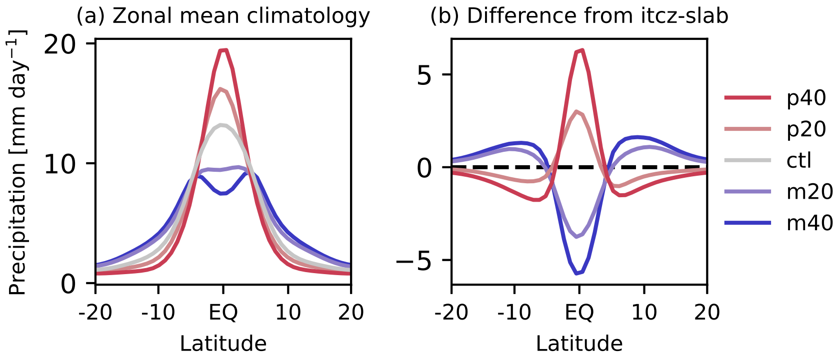

Figure 2. Climatological zonal-mean precipitation for (a) Experiments 1-5 and (b) Experiment 2-5 minus itcz-slab (Experiment 1) for CESM2.

q-flux forcing drives a systematic change in the width of the ITCZ, as intended; heating of the deep tropics leads to narrowing of the ITCZ ("p" for positive deep tropical heating experiments), while cooling of the deep tropics leads to ITCZ widening ("m" experiments). This is visible in terms of the width of the deep precipitation belt (Fig. 2a), and is also reflected in the mass-ITCZ-width metric based on the 500 hPa streamfunction (Fig. 3, see section 2.6, and consistent with other metrics like $P-E$-based width, not shown). Changes in ITCZ width also coincide with changes in peak precipitation strength (Fig. 2); a narrower ITCZ coincides with an increased peak zonal-mean precipitation on and near the equator and reduced precipitation in the rest of the tropics (and the reverse for a widening ITCZ). In the widening ITCZ experiments (especially the one with the largest forcing, m40), the ITCZ splits into separate local zonal-mean precipitation maxima in each hemisphere in some models, including CESM2 (blue line, Fig. 2a).

One aspect that the protocol is designed to address is the linearity of the ITCZ width variations to magnitudes and sign of q-flux forcing. To accomplish this, the experimental protocol has two magnitudes of q-flux forcing that are relatively large locally near the equator, one a factor of 2 larger than the other (peaking at 20 and 40 Wm^{-2}). These q-flux forcings are each applied with positive and negative sign. These constitute four experiments in the current base climate, and a fifth which is a control (no q-flux forcing).

The width of the ITCZ as a function of the magnitude of q-flux forcing magnitude and sign for the four pilot MIP models is shown in Fig. 3. The ITCZ width response is remarkably linear for all four models, though the magnitude of the variation across the experiments varies among the models (the slopes of the lines in Fig. 3; listed in Table 3).

3.2 Global mean temperature and ITCZ width

The q-flux forcing applied in these experiments adds heat to the system in the deep tropics. In order to avoid directly adding net energy in the global mean, the same amount of energy is removed at higher latitudes in each hemisphere, such that the net

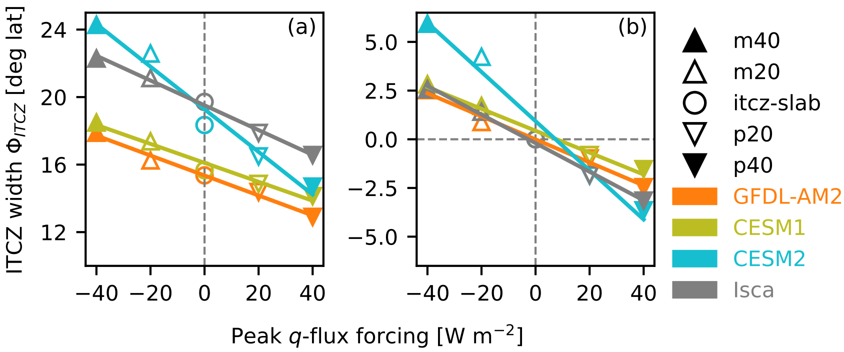

Figure 3. ITCZ mass width as a function of peak q-flux forcing in the control simulations, with present-day CO_2, for all models. (a) Absolute width and (b) width difference from itcz-slab (Experiment 1). ITCZ mass width metric is based on the zero crossing of the 500 hPa streamfunction (section 2.6).

Table 3. Slope of best-fit line to ITCZ width versus q-flux forcing magnitude for current CO_2 levels in each model.

Model	Slope
GFDL-AM2.1	-0.059 $^\circ lat/$W m^{-2}
CESM1.2	-0.056 $^\circ lat/$W m^{-2}
CESM2.0	-0.126 $^\circ lat/$W m^{-2}
Isca	-0.073 $^\circ lat/$W m^{-2}

global addition of heat is zero. Therefore, if the only factor determining global mean temperature were the applied forcing, then we would expect global-mean temperature to remain unchanged across the experiments.

This is, however, not quite the case. Figure 4a shows the global-mean temperature versus ITCZ width for each model and q-flux experiment (all with baseline CO_2 concentrations, and using the mass-based width metric). There is a nearly linear relationship between ITCZ width and temperature across experiments for each model; for all models, temperature increases with widening ITCZ across the experiments. To a large extent, the magnitude of the temperature versus control-ITCZ width-slope is also similar among the three comprehensive models; recall that Isca has no representation of cloud radiative effects. In order to confidently move forward with using this MIP protocol to probing questions about how ITCZ width affects global climate, we first attempt to understand why global mean temperature responds to our protocol despite not adding any energy to the system in the global mean.

There are at least two possible mechanisms that could lead to the relationship between global mean temperature and ITCZ width, each of which we consider in turn. The first is the "radiator fin" mechanism from Pierrehumbert (1995). This mechanism hinges on the notion that cooling to space varies with global temperature most strongly in the subtropical descending branch of the Hadley circulation. In the ascending branch, there is strong compensation between LW and SW cloud feedbacks, and

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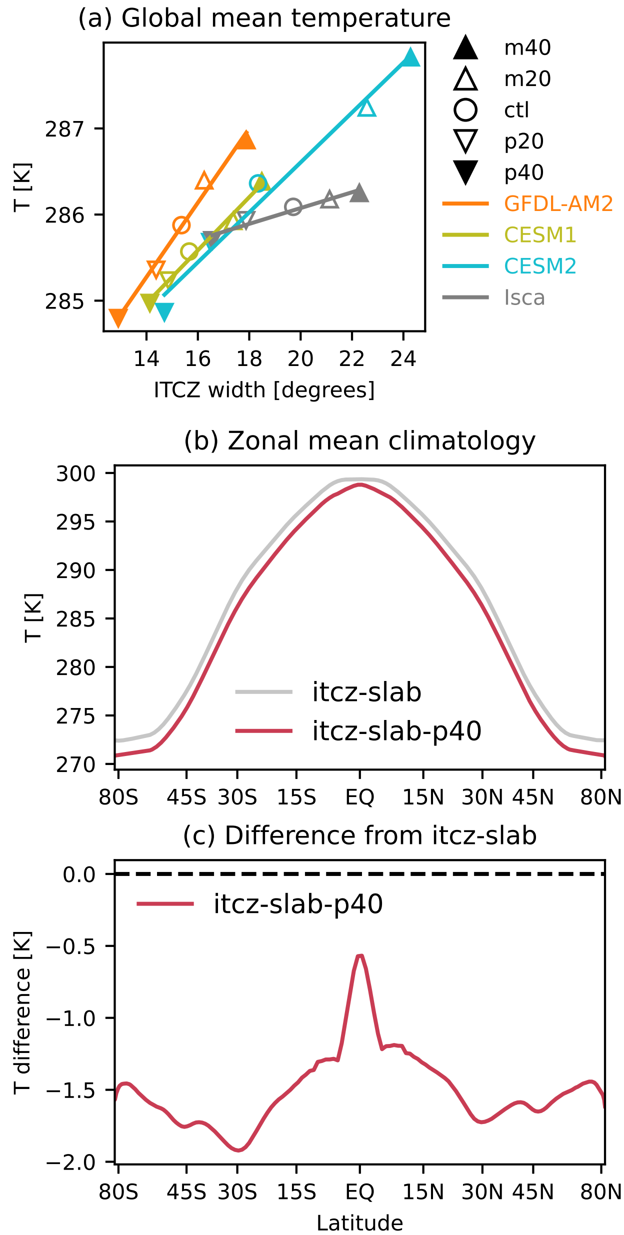

Figure 4. (a) Global mean surface temperature versus ITCZ width in ITCZ MIP experiments, including a regression line for each model. Zonal mean temperature in CESM2 control and decreased (narrow) ITCZ width experiments (itcz-slab-p40); (b) absolute temperature and (c) difference from control.

so sensitivity to climate state is small. Pierrehumbert (1995) developed an heuristic model in which global surface temperature

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decreases as the fractional area of descent increases, because this increases the cooling efficiency of the planet. This would be consistent with higher global-mean temperature for a wider ITCZ.

The ITCZ-MIP pilot models' behavior (Fig. 4a) is consistent with the prediction of Pierrehumbert's radiator fin model. Furthermore, the radiator-fin effect is apparent in the OLR field of ITCZ-MIP experiments (Fig. 5). In the control experiment (Fig. 5a; dashed blue line), OLR peaks just poleward of the latitude where the descending region begins. As the ITCZ narrows (in the p40 experiment; solid blue line), the descending branch extends (or perhaps shifts) equatorward, and the peak OLR increases in strength. The resulting change in TOA net LW (Fig. 5b, solid blue line; note the sign has changed to downwelling positive in preparation for further comparisons below), is a lobe of decreasing downwelling LW (increasing OLR) in the subtropics, which corresponds to a loss of energy by the atmosphere. Coincident with the radiator-fin OLR response, there is also a change in net downwelling SW flux at the TOA which partially compensates; but overall the total change in flux is dominated by the OLR, radiator-fin response in edge of the descending branch abutting the ITCZ. Within the ITCZ itself, the region in Fig. 5 where ω_{500} is upward, larger magnitude changes in both SW and LW flux partially compensate, which is an essential component of the radiator fin mechanism. This compensation occurs to varying degrees among the ITCZ-MIP models. Overall, as the ITCZ narrows, the tropics lose more energy to space via radiative flux, while the Earth gains energy in the extratropics. This effect can be viewed as one aspect of the response to changing ITCZ width, since the equatorward expansion of the descent region is what fills the area that has ascent in the control simulation.

A second potential mechanism offered by the literature is the variation in efficacy of ocean heat uptake on surface temperature with latitude (Kang and Xie, 2014; Rose et al., 2014). These studies showed that when the same q-flux (interpreted as ocean heat uptake in these studies, but nonetheless a form of surface heat flux) is applied at high and low latitudes, global mean temperature increases far more in response to the high-latitude forcing than the low-latitude forcing. As our experimental design is to have a q-flux that integrates globally to zero by compensating deep tropical heating with cooling outside of the deep tropics, the difference in efficacy of these two types of forcing probably contributes to the overall increase in global mean surface temperature. In Fig. 4c, we see that for this experiment where heat is added at the equator and removed in mid- and high-latitudes, near-surface air temperature cools, consistent with the differing efficacy mechanism. In CESM2 (Fig. 4c), the peak cooling occurs near 30° latitude, and polar amplification is modest.

Interestingly, while they did not specifically analyze the width of the ITCZ in their simulations, Kang and Xie (2014) did report on the strength of the Hadley circulation, which (as we will see in the next section) is closely linked to ITCZ width. In particular, heating in the tropics strengthens the Hadley cell and corresponds to a narrowing of the ITCZ, while heating the extratropics weakens the Hadley cell, probably corresponding to a widening of the ITCZ. The ITCZ-MIP prescribed forcing can be thought of as a superposition of tropical heating and extratropical cooling (or vice versa), and to the extent that the Hadley cell responses are additive and correspond to ITCZ width changes, the variations in ITCZ width we would infer from Kang and Xie (2014) agree in sign with our experiments. Furthermore, the change in net TOA fluxes in the tropics and extratropics in our experiments are also consistent with their framework.

The implications for interpreting ITCZ-MIP experiments are that the compensating q-fluxes in the extra-tropics, included to avoid directly adding energy in the global-mean and thus a net climate forcing, in some sense might produce their own impacts

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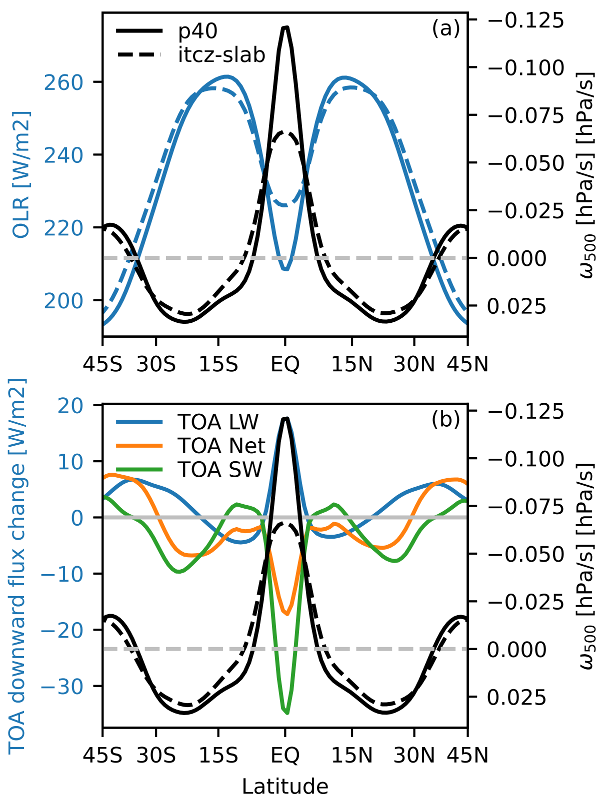

Figure 5. TOA radiative fluxes and ω_{500} for itcz-slab-p40 compared to itcz-slab experiments for CESM2. (a) OLR and ω_{500} in each simulation, focusing on the tropics. (b) Changes in downwelling LW, SW, and net radiative fluxes at the TOA and ω_{500} for itcz-slab and itcz-slab-p40 simulations.

on global climate, which it may not be appropriate to view as impacts of ITCZ width variations. On the other hand, the changes in Hadley cell in Kang and Xie (2014) could also be seen as another pathway through which the additional surface heat fluxes actually force the ITCZ width to change. Therefore, we proceed with appropriate caution, bearing this ambiguity in mind.

In summary, there are at least two mechanisms which could explain the unanticipated relationship between ITCZ width and global mean surface temperature for our itcz-slab experiments: the increase in LW cooling to space as the area of the descent region increases (the radiator fin mechanism) and the higher efficacy of extratropical relative to tropical ocean heat uptake.

3.3 ITCZ strength and width

A key role of the ITCZ in global circulation is that it is the location of mean ascent into the tropical upper troposphere. The strength of the ITCZ, in terms of the mass-flow of air, is a key driver of global circulation. In climate model simulations of global warming, the change in strength is anti-correlated to the projected change in ITCZ width across models, though

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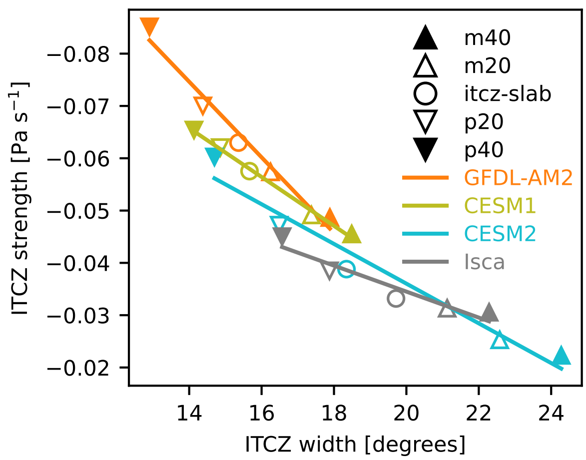

Figure 6. Strength versus width of the ITCZ for the present-day CO_2 simulations of all models.

slightly more models project decreasing than increasing ITCZ strength (Byrne et al., 2018). In this section, we document the relationship between strength and width in the pilot ITCZ-MIP simulations.

We quantify the ITCZ strength as the total mass transport divided by total area, or the bulk vertical pressure velocity for the ITCZ following Byrne et al. (2018),

$$\omega_{ITCZ} = -g\Psi_{ITCZ}/A_{ITCZ}. \tag{6}$$

Among the ITCZ-MIP experiments with control CO_2 concentration, ITCZ strength and width have a consistent anti-correlation: the narrower the ITCZ, the stronger it is, both across experiments within each model and also among models (Fig. 6).

One might be concerned that this relationship could be more an inadvertent effect of the q-flux forcing that drives the variation in ITCZ width in our experiment, rather than a fundamental relationship between ITCZ width and strength themselves, since adding heat directly to the ITCZ could increase ITCZ strength as well as ITCZ width. However, even setting aside the experiments with q-fluxes added to change ITCZ width and instead comparing among control simulations in different models, the strong inverse relationship between strength and width remains. This preliminary finding prompts an intriguing question that could be investigated with a full-scale ITCZ-MIP containing more than climate models: is the inverse relationship between ITCZ strength and width robust within and across climate models? If so, what is its mechanism? And why does the multi-model mean response (Byrne et al., 2018) differ?

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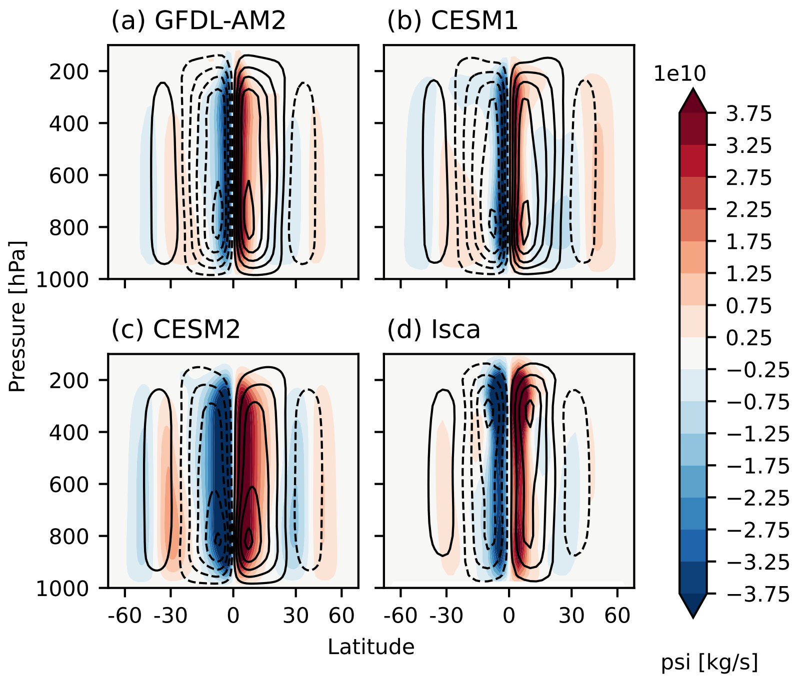

Figure 7. The time- and zonal-mean mass streamfunction for the slab control run (black contours in all panels) and the difference between the experiments with $A = 40$ W m^{-2} and the slab control run (shading) for all four models.

4 Impact of ITCZ width on climate

265 One motivation for the ITCZ-MIP is to examine the effect that variations of ITCZ width have on other aspects of climate. In this section we document some initial findings in the pilot ITCZ-MIP simulations. First, we consider the response to varying ITCZ width while holding CO_2 concentrations fixed; then, we examine the effects on climate as CO_2 concentrations increase.

4.1 Effects of ITCZ width on Hadley cell width and midlatitude jet position

Tropical deep convection is the engine of the global atmospheric circulation, so we might expect that changes in the width of this convection could affect circulation at higher latitudes. In all four models of the pilot MIP, a narrower ITCZ is associated with an overall narrower Hadley cell (Fig. 7). Furthermore, it is also associated with an equatorward shift in the eddy-driven jet (Fig. 8). The responses in all four pilot ITCZ-MIP models are both broadly consistent with the findings from experiments with the GFDL AM2.1 model in an aquaplanet configuration with prescribed SSTs, in which varying deep tropical SSTs induced changes in ITCZ width, Hadley cell width, and eddy-driven jet location (Watt-Meyer and Frierson, 2019).

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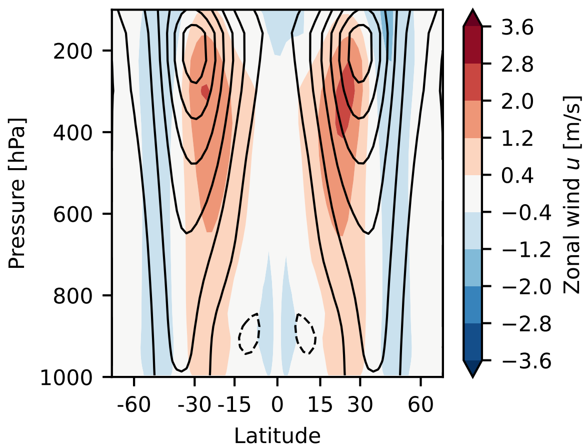

Figure 8. The time- and zonal-mean zonal wind for the slab control run (black contours) and the difference between the experiment with $A = 40$ W m^{-2} and the slab control run (shading) for GFDL-AM2.

4.2 Increased CO_2

Another motivation for investigating ITCZ width is the indication of its narrowing in simulations of global warming in comprehensive climate models and in observations of the real world. The hypothesis posed by Webb and Lock (2020) would be consistent with a wider ITCZ that coincides with reduced low-level cloud radiative effect and less positive feedbacks, and thus lower climate sensitivity; conversely, a narrower ITCZ with stronger low-level cloud radiative effects and more positive low-level cloud feedbacks would have higher climate sensitivity. This hypothesis was supported in aquaplanet experiments where tropical deep convection was varied by altering longwave cloud heating rates, with the HadGEM2-A model. With this hypothesis in mind, we return to our four pilot ITCZ-MIP models (where ITCZ width is forced by q-fluxes applied to slab oceans), and examine the simulations in which CO_2 concentrations increase from base states with differing initial ITCZ width.

ITCZ width itself does not consistently narrow with CO_2-driven warming in the pilot ITCZ-MIP simulations (on the y-axis of Fig. 9, values greater than zero indicate widening ITCZ while values less than zero indicate a narrowing ITCZ). In CESM2 and Isca simulations with narrow base climate ITCZ, the response to increased CO_2 is widening. In CESM2, GFDL-AM2, and Isca simulations with wide base climate ITCZ, the response to increased CO_2 is narrowing. For GFDL-AM2 with narrow base climate ITCZ and for all CESM1 simulations, ITCZ width stays about the same with increasing CO_2.

Within each model, though, there is an anti-correlation between ITCZ width in the base state and the change in ITCZ width as CO_2 increases (Fig. 9a). The magnitude of the relationship varies greatly among models: from very small in CESM1, moderate in GFDL-AM2, to large in Isca and CESM2. Overall this suggests a preferred ITCZ width in each model, at some intermediate value, though with strongly varying degrees of affinity to the preferred width among the four models.

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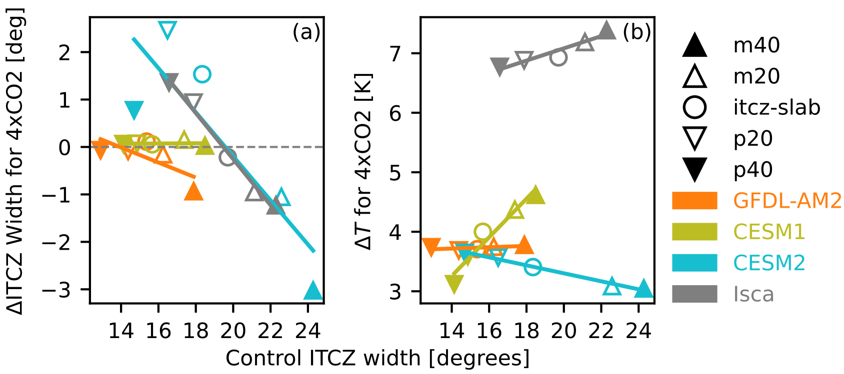

Figure 9. Response to an abrupt CO_2 increase of (a) ITCZ width and (b) global mean surface temperature plotted against ITCZ width in control CO_2 simulations.

Previous authors have hypothesized that ITCZ width could affect climate sensitivity, and the ITCZ-MIP experiments provide an intervention with which to test this hypothesis. Among the four pilot ITCZ-MIP models, the effect on climate sensitivity of ITCZ width spans the full range of possibilities – increase, decrease, to no substantive effect (Fig. 9b). While the effect in CESM2 is consistent in direction with the expectation from Webb and Lock (2020)'s hypothesis, it is inconsistent with all other models, even including CESM1. Recalling that Isca lacks cloud radiative feedbacks, and thus we should take care interpreting its climate sensitivity, its response is nonetheless similar to CESM1. So even the three pilot MIP models with standard representations of radiation span the full range of possible effects of ITCZ width on climate sensitivity.

A more consistent pattern of behavior across the pilot MIP models is the relationship between the response of ITCZ width and strength, which are strongly anti-correlated in response to CO_2 increase (not shown). This is consistent with the their relationship within the base climate state (Section 3.3) and with the response to global warming in CMIP5 (Byrne et al., 2018, Fig. 4b).

5 Discussion and Implications

The ITCZ is important for global climate, both locally in the tropics and as the source for teleconnections to the extratropical atmosphere. Yet the variability and change of its width are uncertain, not well understood, and lacking in fundamental theory. We begin to address this by developing a protocol for changing ITCZ width and demonstrating its successful application to multiple climate models. In response to added heat flux at the surface in the deep tropics, the width of the ITCZ decreases; conversely, in response to reduced heat flux, the ITCZ width increases. The sign and magnitude of the ITCZ width response to the surface heat flux forcing is linear in sign and magnitude.

The ITCZ-MIP protocol for forcing ITCZ width to change is inspired by and consistent with earlier work examining differences in ITCZ width among climate models from a diagnostic energy budget perspective. In particular, the idea for perturbing ITCZ width by adding (or removing) energy from the deep tropics originated in the analysis of Byrne and Schneider (2016b).

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While previous studies have generated changes in ITCZ width in individual climate models, this is the first study, to the authors' knowledge, in which a single protocol is demonstrated to successfully change ITCZ width in more than one climate model.

Findings from this pilot MIP prompt at least three new questions which could be addressed by future work. First, the relationship between ITCZ width and strength is consistent across experiments and among the pilot MIP climate models, suggesting that it could be a robust feature of the ITCZ. Adequately establishing robustness among climate models would require analyzing a larger set of climate models, as well as further examination of the possibility that it could be an artifact of the protocol. The protocol and its successful generalization to multiple climate models demonstrated here can provide a foundation on which future work can build, into a MIP with a larger number of models in order to increase ability to infer robustness.

To demonstrate disagreement among models, on the other hand, a small set of climate models is sufficient; the pilot MIP clearly reveals that models disagree about the relationship of climate sensitivity to base-state ITCZ width, even in sign. The second question, then, is why? Further investigation of how ITCZ width affects climate feedbacks, especially cloud feedbacks, could delve into the mechanisms and processes underlying this disagreement.

The third question is, what, exactly, the mechanism of action is for the consistent changes in ITCZ width that are generated by the addition of heat via surface fluxes. Overall, the ITCZ-MIP protocol for generating changes in ITCZ width reveals rich differences in behavior among models. Pursuing answers to these questions – even with simple experiments run in an idealized configuration – could be a fruitful path to fuller theories and deepened understanding of what controls the width of the ITCZ.

Code and data availability. Monthly 2-D model output from the pilot MIP simulations and code (in the form of python notebooks) to generate all figures and the additional q-flux forcing are available from https://github.com/apendergrass/width-itcz-mip (doi:10.5281/zenodo.10558341).

Author contributions. AGP and MPB conceptualized the project initially, MJW provided conceptual input throughout the evolution of the project, and OWM provided essential early input. MPB, AGP, and OWM led the methodology, investigation and analysis to develop the protocol. Model simulations were contributed by MPB (CESM1.2), AGP (CESM2.0), OWM (GFDL-AM2.1), and PM (Isca). OWM led the data curation and software development for analyzing the pilot MIP simulations. OWM led the initial draft of data visualizations, and AGP revised and finalized the visualizations. OWM drafted the protocol description and section 4.1 of the original manuscript draft, PM organized versions of the components of the original draft, and AGP led the writing of the rest of the original draft of the manuscript. All authors contributed to review and editing of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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