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**Key Points:**

- In response to $CO_2$ doubling, the SST contrast between the hemispheres increases and the ITCZ, in general, shifts poleward
- Even with no change in the energy flux equator, there can be a significant ITCZ shift from changes in the total GMS (TGMS)
- Large sensitivity of ITCZ response to changes in TGMS calls for better understanding of the physics determining the tropical TGMS

**Supporting Information:**

- Supporting Information S1

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# A model intercomparison of the tropical precipitation response to a $CO_2$ doubling in aquaplanet simulations

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**Abstract** In the present-day climate, the mean Intertropical Convergence Zone (ITCZ) is north of the equator. We investigate changes in the ITCZ latitude under global warming, using multiple atmospheric models coupled to an aquaplanet slab ocean. The reference climate, with a warmer north from prescribed ocean heating, is perturbed by doubling $CO_2$. Most models exhibit a northward ITCZ shift, but the shift cannot be accounted for by the response of energy flux equator where the atmospheric energy transport ($F_A$) vanishes. The energetics of the simulated circulation shifts are subtle: changes in the efficiency with which the Hadley circulation transports energy, the total gross moist stability ($\Delta m$), dominate over mass flux changes in determining $\delta F_A$. Even when $\delta F_A \approx 0$, the ITCZ can shift significantly due to changes in $\Delta m$, which have often been neglected previously. The dependence of ITCZ responses on $\delta\Delta m$ calls for improved understanding of the physics determining the tropical $\Delta m$.

## 1. Introduction

The present-day Earth's climate exhibits a substantial hemispheric asymmetry, with the Northern Hemisphere (NH) warmer than the Southern Hemisphere (SH), which has been suggested to be a result of a northward cross-equatorial ocean heat transport [*Kang et al.*, 2015]. This is also the reason that the band of heavy rainfall in the tropics, called the Intertropical Convergence Zone (ITCZ), is located on the northern side of the equator [*Frierson et al.*, 2013; *Marshall et al.*, 2014]. Consequently, the rising branch of the annual-mean Hadley circulation (HC) is located in the northern tropics, giving rise to the stronger southern HC than the northern HC [*Dima and Wallace*, 2003]. As a result of the increase in greenhouse gas concentration, the NH is projected to warm more than the SH, which would amplify the existing hemispheric asymmetry [*Friedman et al.*, 2013].

Does the ITCZ shift toward the differentially warmed NH in response to increasing $CO_2$? If the Earth's climate was hemispherically symmetric, the nearly uniform radiative forcing would not be able to shift the ITCZ to make it favor one hemisphere. However, our current climate is hemispherically asymmetric with a warmer NH and the ITCZ in the NH. Then, the $CO_2$ radiative forcing may lead to a meridional ITCZ shift due to radiative feedback associated with water vapor and clouds [*Kang et al.*, 2008; *Shaw et al.*, 2015]. Indeed, in aquaplanet simulations with the Geophysical Fluid Dynamics Laboratory (GFDL) High-Resolution Atmospheric Model (HiRAM), with a warmer NH reference state, the ITCZ shifts northward when perturbed by a doubling of $CO_2$ [*Merlis et al.*, 2013a]. It is of interest to examine the robustness of the ITCZ response to increased $CO_2$ under the hemispherically asymmetric reference state. As $CO_2$ concentration is increased, the hemispheric asymmetry in the surface temperature will be amplified due to the positive water vapor feedback, which may lead to a robust ITCZ shift toward the warmer hemisphere. In contrast, the outgoing longwave radiation (OLR) in the warmer hemisphere will increase more, leading to more energy loss in the warmer hemisphere, which may lead to a robust ITCZ shift toward the cooler hemisphere. Indeed, in Coupled Model Intercomparison Project phase 3 (CMIP3) slab ocean simulations of global warming, models that have more anomalous warming in the NH extratropics tend to show more increase in OLR there, contributing to a southward ITCZ shift [*Frierson and Hwang*, 2012]. Furthermore, the cloud radiative effects may act to preferentially warm either hemisphere, raising a possibility of uncertainty across models. Another complication may arise from the dependence of the efficiency with which the HC transports energy, known as the gross moist stability, on climate changes [*Hill et al.*, 2015], as we shall see.

To eliminate complications from realistic boundary conditions while keeping the hemispherically asymmetric state, we utilize atmospheric general circulation models coupled to an aquaplanet slab ocean and prescribe the northward ocean heat transport.

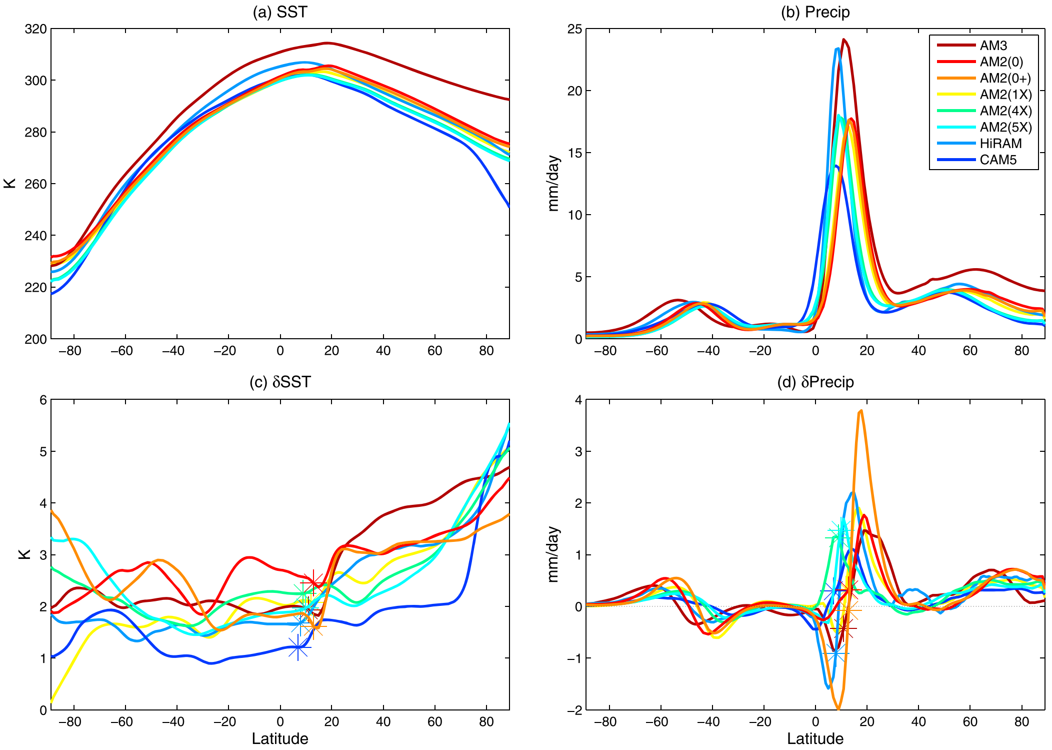

**Figure 1.** The zonal-mean (a) sea surface temperature (SST; K) and (b) precipitation (mm/d) in the reference (1×$CO_2$) integration. The response of the (c) SST and (d) precipitation to 2×$CO_2$. The asterisks indicate the ITCZ latitude in the reference (1×$CO_2$) integration.

## 2. Model Description and Experimental Design

### 2.1. Models

To investigate the robustness of the results, four different models are employed that are coupled to an aquaplanet slab ocean of 2.4 m depth: GFDL-Atmosphere Model version 2 (AM2) [*Anderson et al.*, 2004], GFDL-AM3 [*Donner et al.*, 2011], GFDL-HiRAM [*Zhao et al.*, 2009], and National Center for Atmospheric Research Community Atmosphere Model version 5 (CAM5) [*Medeiros et al.*, 2016]. In all models, the sea surface temperature (SST) is allowed to drop below freezing temperature, without forming any sea ice. There is no aerosol in our simulations. All simulations are run under perpetual equinox conditions and are integrated for 10 years, with a spin-up period of 2 years. The details of models are given in the supporting information.

To increase the range of simulations, we perturb one of the convection scheme parameters that modify the fraction of precipitation that occurs as large-scale condensation as opposed to convection in GFDL-AM2 [*Tokioka et al.*, 1988]. The standard case is denoted as AM2(1×), and those with a modified convection scheme parameter are specified by a different prefix in the parenthesis. It is noted that the key results do not depend on including the perturbed AM2 simulations.

### 2.2. Experiment Setup

The experiments are designed to study the mechanisms by which the off-equatorial ITCZ responds to a doubling of $CO_2$. To locate the ITCZ in the NH as in the Earth's current climatology, a prescribed amount of heat transport convergence within the slab ocean is moved from poleward of 40°S to poleward of 40°N with the peak value of 40 $Wm^{-2}$, corresponding to a northward flux of 2.33 PW across the equator, as in *Kang et al.* [2008]. All other aspects of the boundary conditions and forcing are hemispherically symmetric. In response to the northward ocean heat transport, the NH becomes warmer than the SH and the ITCZ is located in the northern tropics in all models (Figures 1a and 1b). However, even though the same magnitude of ocean heat transport is prescribed, the resultant SST distribution and the exact ITCZ location vary widely across models.

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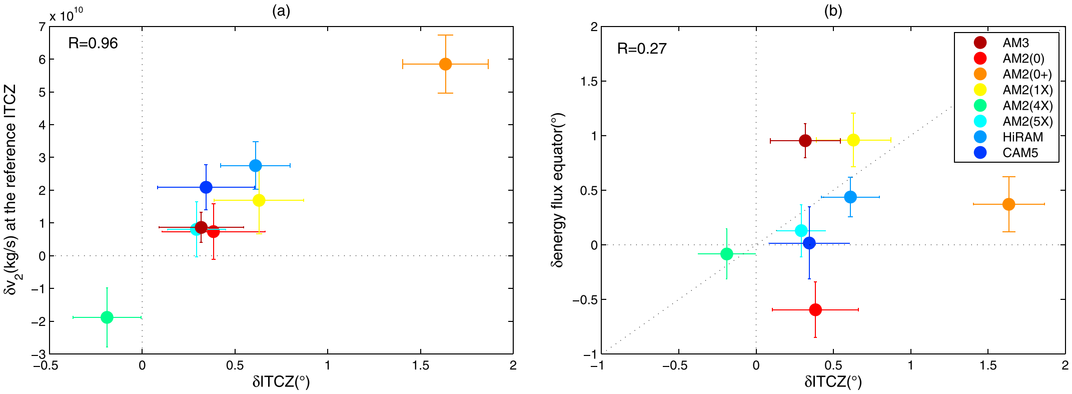

**Figure 2.** (a) The ITCZ response (in degrees) and the change in lower level mass flux ($\delta v_2$; in kg/s) at the reference ITCZ location. (b) The ITCZ response and the response of energy flux equator (in degrees). The horizontal and vertical bars indicate the 90% confidence level based on the monthly variation. In each plot, the correlation coefficient between the two variables is shown at the top left corner.

The difference in the mean SST between the hemispheres exhibits a wide range from 11.96 K in CAM5 to 20.05 K in AM3. The ITCZ location, obtained by differentiating the zonal-mean precipitation with respect to latitude and linearly interpolating to find the zero crossing, ranges from 7.86°N in CAM5 to 13.78°N in AM2(0). The large spread in the reference climate with the same prescribed ocean heat transport is interesting in and of itself [*Lee et al.*, 2008; *Rose et al.*, 2014], but this is beyond the scope of our study.

The reference climate, in which the NH is warmer than the SH, is then perturbed by a $CO_2$ doubling. The $CO_2$ concentration of the reference climate is 348 ppm. The responses to a doubling of $CO_2$ are obtained by differencing the climatology of the reference integration ($1\times CO_2$) from that of the doubled $CO_2$ integration ($2\times CO_2$) and are denoted as $\delta$.

## 3. Results

When the $CO_2$ concentration is doubled, the climatologically warm NH warms more than the climatologically cold SH in all models (Figure 1c). The difference in the SST between the hemispheres is intensified whether it is measured with respect to the equator or the reference ITCZ latitude. We note that this differential warming of the NH occurs without the surface albedo feedback, a widely discussed factor in Arctic climate changes in comprehensive simulations [*Screen and Simmonds*, 2010]. Consistent with a larger hemispheric SST contrast, the ITCZ in most models shifts northward but with a large model spread (Figure 2a). The largest northward shift, found in AM2(0+), is 1.64°, whereas AM2(4×) exhibits a slight southward shift of 0.19°. When the SST response is averaged 5° to the north and south of the reference ITCZ latitude, there is no consistent trend: four out of seven models exhibit a more warming on the northern flank of the reference ITCZ, whereas three models exhibit an opposite response and one model (AM2(1×)) shows little contrast. Therefore, some models warm more on the southern flank of the reference ITCZ, yet the ITCZ shifts northward, implying that the local SST response cannot explain the ITCZ response. The ITCZ response does have a modest correlation of 0.40 with the response of the latitude of maximum surface moist static energy, but one model exhibits an opposite response between the two variables. Hence, we turn to the energy flux perspective to understand the ITCZ response.

Since the response of tropical precipitation is dominated by the response of mean moisture convergence, the ITCZ response is closely associated with the response of lower level mean mass flux. That is, an anomalous northward lower level mass flux at the reference ITCZ corresponds to the northward ITCZ shift and vice versa (Figure 2a). The lower level time- and zonal-mean mass flux, $v_2$ (with the subscript 2 denoting the lower level), can be related to the atmospheric energy transport, $F_A$, by adopting the concept of total gross moist stability, which is defined as the amount of total atmospheric energy transport per unit mass transport ($\Delta m \equiv -F_A/v_2$) following *Kang et al.* [2009]:

$$v_2 = -F_A/\Delta m, \tag{1}$$

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with the vertical integral of total meridional moist static energy transport $F_A$. Via the steady state zonal-mean atmospheric energy budget, $F_A$ is related to the net energy input to the atmosphere as $R_{\mathrm{TOA}} + O = \nabla \cdot F_A$, where $R_{\mathrm{TOA}}$ is the net downward radiative flux at TOA and $O$ is the upward surface energy flux. In our slab ocean experiments, $O$ is the prescribed amount of heat transport convergence and its change is zero by construction. The lower level mass flux is $v_2 = \int_{p_m}^{p_0} v dp/g$, with $p_0$ as the surface pressure and $p_m$ as the midtropospheric level where a vertically integrated mass flux attains its maximum. Positive $v_2$ indicates a northward lower level mass flux and vice versa. The negative sign is included in equation (1) for positive $\Delta m$ to indicate a larger-energy transport in the upper level than in the lower level. In the reference climate, $p_m$ generally falls between 800 and 600 hPa. In response to 2×$CO_2$, $p_m$ consistently increases in all models but by less than 3%. Since the effect of changing $p_m$ has negligible impact on the estimate of $\Delta m$, $v_2$ is computed with the $p_m$ fixed at 700 hPa for simplicity.

Since our reference climate is hemispherically asymmetric, there is the potential for the response of net TOA radiative fluxes to 2×$CO_2$ to be hemispherically asymmetric due to radiative feedback. Then, the HC will respond to transport energy across its rising branch in the reference state to balance the atmospheric energy budget. Equation (1) indicates that $\delta F_A$ can arise from changes in either $v_2$ or $\Delta m$. That is,

$$\delta F_A = -\Delta m \cdot \delta v_2 - \delta \Delta m \cdot v_2 - \delta \Delta m \cdot \delta v_2. \tag{2}$$

In what follows, we describe the implications of limiting cases of equation (2) for ITCZ shifts: $\delta \Delta m \approx 0$ and $\delta v_2 \approx 0$, and diagnose the simulated changes in the components of equation (2). In one limiting case, assuming a constant $\Delta m$, the response of atmospheric transport can be directly linked to $\delta v_2$; hence, the ITCZ shifts in proportion to $\delta F_A$ [e.g., *Kang et al.*, 2008; *Donohoe et al.*, 2014]. As some thermal perturbations create hemispheric asymmetry in the energy input to the atmospheric column, the HC responds to transport energy from the hemisphere with a surplus of energy to the hemisphere with a deficit of energy. Even when the hemispheric asymmetry is introduced in the extratropics, its effect can reach the tropics through the eddy energy fluxes [*Kang et al.*, 2009]. In fact, the extratropical energy input has been shown to be more effective at affecting the ITCZ location than the low-latitude energy input due to nonlinear cloud radiative effects [*Seo et al.*, 2014]. In general, the energy is transported in the direction of upper branch of the HC (i.e., $\Delta m > 0$), so abundant moisture in the lower troposphere is transported in the opposite direction to the energy (i.e., $\delta v_2 \propto -\delta F_A$). Hence, the ITCZ response is negatively correlated with $\delta F_A$ at the reference ITCZ. In the other limiting case, equation (2) indicates that $\delta F_A$ can solely arise from $\delta \Delta m$. Even with $\delta v_2 = 0$, that is, with no shift in the rising branch of the HC, there still can be changes in $F_A$: $\Delta m$ can change from the vertical redistribution of moist static energy, changes in the vertical structure of the overturning circulation, or eddy energy flux changes. As the relative importance of $\delta \Delta m$ for determining $\delta F_A$ increases, the previous energy flux perspective will fail to predict the ITCZ response.

Previous analyses have focused on relating the ITCZ response to the response of vertically integrated atmospheric energy flux $F_A$ (i.e., the limiting case when $\delta \Delta m \approx 0$). If the meridional profile of $F_A$ is linear in the deep tropics and its meridional slope changes little to 2×$CO_2$, $\delta F_A$ at the reference ITCZ can be used to infer the shift of the energy flux equator ($\varphi_e$), where $F_A$ is zero. That is, a positive $\delta F_A$ at the reference ITCZ is associated with a southward shift of $\varphi_e$ and vice versa. In our doubling $CO_2$ experiments, the ITCZ response is not so well correlated with the response of $\varphi_e$ (Figure 2b). In AM2(0), the ITCZ shifts to the north but $\varphi_e$ shifts to the south. In CAM5, a significant ITCZ shift to the north is accompanied by little shift in $\varphi_e$. Overall, the correlation coefficient between $\delta$(ITCZ) and $\delta(\varphi_e)$ is only 0.27. Thus, the response of energy flux equator does not account for the ITCZ response in these aquaplanet simulations. In general, a shift of $\varphi_e$ can be caused by either changes in the cross-equatorial $F_A$ [e.g., *Kang et al.*, 2008; *Donohoe et al.*, 2014] or changes in the net energy input to the equatorial atmosphere, equivalent to $\nabla \cdot F_A$ [see *Bischoff and Schneider*, 2014, Figure 1]. In our simulations, the cross-equatorial $\delta F_A$ is only modestly correlated with the ITCZ response by a correlation coefficient of $-0.42$ (Figure S1 in the supporting information). The two models (AM2(0) and AM2(1×)) exhibit a response opposite to the expectation of anticorrelated changes in $\delta F_A$ and the change in ITCZ latitude: the positive $\delta F_A$ at the equator is accompanied by the northward ITCZ shift.

Based on equation (2), the simulated change in atmospheric energy transport ($\delta F_A$; black) is decomposed into the term due to the change in lower level mass flux ($-\Delta m \cdot \delta v_2$; blue) and that due to the change in total

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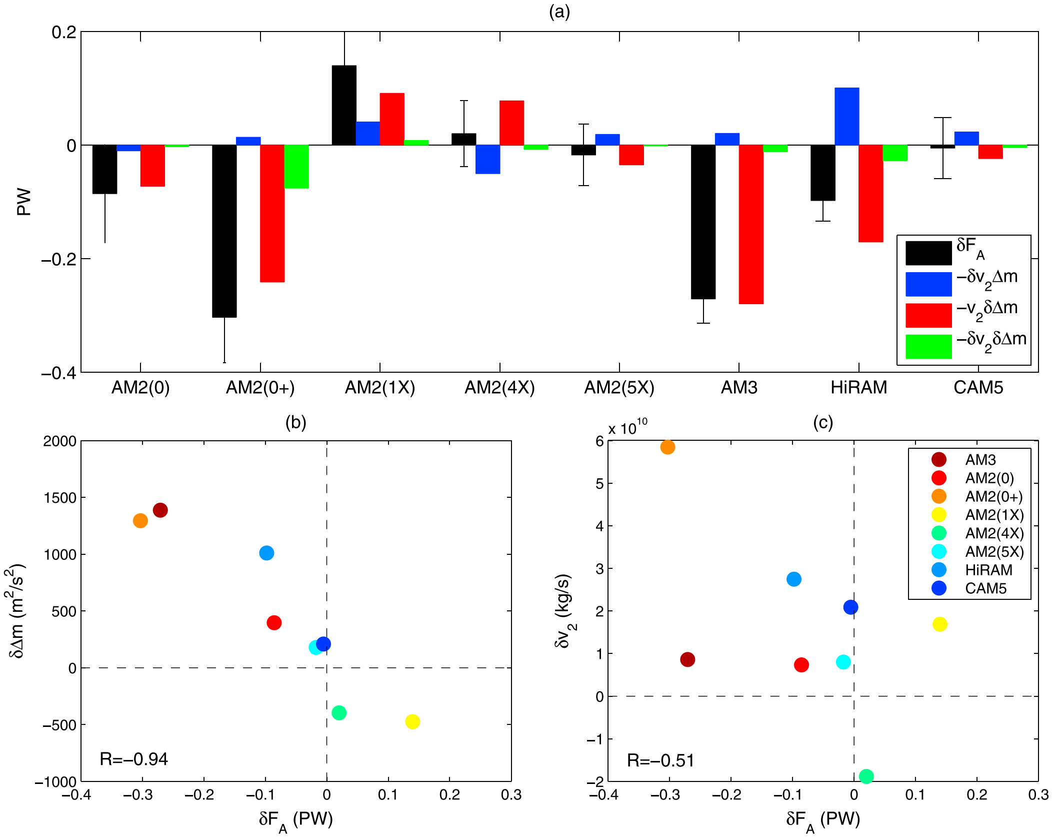

**Figure 3.** (a) Decomposition of the anomalous atmospheric energy flux ($\delta F_A$; black) into the term due to the change in lower level mass flux ($-\delta v_2 \Delta m$; blue), due to the change in total gross moist stability ($-v_2 \delta\Delta m$; red), and the cross term ($-\delta v_2 \delta\Delta m$; green). The vertical bars indicate the 90% confidence level of $\delta F_A$ based on the monthly variation. All are in the unit of PW. The relationship between the anomalous atmospheric energy flux ($\delta F_A$ in PW) and (b) the total gross moist stability change ($\delta\Delta m$; $m^2/s^2$) and (c) the lower level mass flux change ($\delta v_2$; kg/s). In Figures 3b and 3c, the correlation coefficient between the two variables is indicated at the bottom left corner. All are diagnosed at the reference ITCZ.

gross moist stability ($-\delta\Delta m \cdot v_2$; red), as shown in Figure 3a. The decomposition is conducted at the latitude of reference ITCZ of the respective model. Note that, at the reference ITCZ, $\Delta m$ is well defined because the maximum mass convergence arises in the winter hemisphere, on the equatorward side of the rising branch of the HC where $v_2 = 0$. The range of 90% confidence level of $\delta F_A$ is depicted by vertical bars. If the vertical bars cross zero, $\delta F_A$ is regarded as zero. The cross term (green) is typically small so that the relative importance between $\delta v_2$ and $\delta\Delta m$ can be examined. In all models, $\delta\Delta m$ (red) is more important at determining $\delta F_A$ (black) than $\delta v_2$ (blue), indicating that the assumption of negligible $\delta\Delta m$ in previous studies is not valid in our doubling $CO_2$ experiments. Indeed, the correlation between $\delta F_A$ and $\delta\Delta m$ is over 0.9, whereas the correlation between $\delta F_A$ and $\delta v_2$ is only 0.5 (Figures 3b and 3c). Given that $\Delta m$ increases away from the ITCZ in its climatology [*Held*, 2001], one might think that $\Delta m$ changes as a response to the ITCZ shift. However, the spatial distribution of $\Delta m$ does not simply undergo a meridional shift but exhibits a significant modulation at all latitudes, implying that $\delta\Delta m$, in part, causes the ITCZ shift. Therefore, the shift of the ITCZ in response to $2\times CO_2$ cannot be understood without accounting for the change in total gross moist stability in the tropics.

Let us first examine the cases with $\delta F_A \approx 0$ at the reference ITCZ: AM2(4×), AM2(5×), and CAM5 (Figure 3a). In previous studies where $\Delta m$ is assumed fixed, no ITCZ shift is expected when $\delta F_A = 0$. However, with significant changes in $\Delta m$, as in our set of simulations, zero $\delta F_A$ can still result in changes in $v_2$ and accompany a shift in the ITCZ. For reference, $\Delta m$ in $1\times CO_2$ at the reference ITCZ and its response to $2\times CO_2$ is provided in Figure S2. In the case of $\delta F_A = 0$ and assuming a small cross term, $\delta v_2 = -v_2 \delta\Delta m / \Delta m$. Note that $v_2 > 0$ at the reference ITCZ. As the efficiency with which the circulation transports energy decreases (increases), $\delta v_2 > 0$ ($< 0$),

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indicating a northward (southward) ITCZ shift. For example, AM2(4×), in which $|\Delta m|$ increases in response to $2\times CO_2$, exhibits a southward ITCZ shift. In contrast, $|\Delta m|$ is reduced in AM2(5×) and CAM5, and the ITCZ is shifted northward. The sign of $\delta\Delta m$ at the reference ITCZ differs across models (Figure 3b). As the sign of $\delta\Delta m$ is determined by the ratio between the changes in the total energy transport in the upper level and that in the lower level, how the convection responds to $2\times CO_2$ will affect $\delta\Delta m$. For instance, if the convection becomes deeper, more energy can be transported by the upper branch, potentially leading to an increase of $\Delta m$. Indeed, the gross moist stability defined with the mean energy transport, rather than the total energy transport, consistently increases with $2\times CO_2$, as in CMIP3 and CMIP5 simulations [*Chou et al.*, 2013; *Feldl and Bordoni*, 2016]. However, changes in eddy transport and cloud radiative properties can overwhelm the effect of a deepening of convection and may lead to a reduction in $\Delta m$ in some models. Hence, uncertainties in cloud modeling and convection schemes can cause uncertainties in $\delta\Delta m$, creating a large model spread. This illustrates the importance of accounting for the changes in $\Delta m$ when assessing the tropical precipitation response to the nearly uniform $CO_2$ radiative forcing.

Let us now examine the cases with nonzero $\delta F_A$ at the reference ITCZ. AM2(1×) exhibits a significantly positive $\delta F_A$, whereas AM2(0), AM2(0+), AM3, and HiRAM exhibit a significantly negative $\delta F_A$ (Figure 3a). This contrast can be largely understood from the differences in the response of cloud radiative effect (**δ**CRE), as shown in Figure S3. For instance, AM2(1×) with the largest northward $\delta F_A$ exhibits a substantial warming from the cloud responses in the southern subtropics relative to the northern subtropics, whereas AM3 with the largest southward $\delta F_A$ exhibits a widespread warming in the northern extratropics. It clearly illustrates that the nearly uniform $CO_2$ radiative forcing is able to create hemispheric asymmetry in the response of net TOA radiative fluxes, which will then require changes in $F_A$ at the reference energy flux equator.

In the previous energy flux perspective where $\Delta m$ is assumed fixed and positive, the nonzero $\delta F_A$ is expected to be anticorrelated with the ITCZ response. We note three distinct responses in which this perspective is insufficient to explain our results. First, in AM2(0+), AM3, and HiRAM, $\delta F_A$ is negative and $\delta v_2$ is positive, seemingly consistent with the previous studies. In fact, $\Delta m$ is negative at the latitude of reference ITCZ (Figure S2), so that $\delta v_2$ is predicted to be negative under the assumption of a fixed $\Delta m$ (Figure S4). It turns out that the negative $\delta F_A$ mostly results from substantial increases in $\Delta m$. Changes in $\Delta m$ result in larger $\delta F_A$ than needed, which is offset by a positive $\delta v_2$ (i.e., a northward ITCZ shift). Second, AM2(0) is consistent with previous studies in a sense that $\Delta m > 0$ and a negative $\delta F_A$ accompanies a positive $\delta v_2$. The simulated $\delta v_2$ and the predicted $\delta v_2$ under the assumption of a fixed $\Delta m$ have the same sign (Figure S4). However, $\delta\Delta m$ dominates over $\delta v_2$ in determining the changes in $F_A$, so that the simulated $\delta v_2$ is much weaker than the prediction. Third, in AM2(1×), a positive $\delta F_A$ is produced by decreases in $\Delta m$. Changes in $\Delta m$ are not large enough, requiring a positive $\delta v_2$ (i.e., a northward ITCZ shift). In all of our simulations, $\delta F_A$ mostly arises from $\delta\Delta m$ rather than $\delta v_2$, which demonstrates that changes in the tropical $\Delta m$ are important across the range of simulated changes in energy transport.

## 4. Conclusions

In response to increasing $CO_2$, the global-mean surface temperature and precipitation will increase. However, the pattern of these changes has large uncertainties despite their importance for regional climate projections. In this study, we investigate how the pattern of tropical precipitation would change in response to a doubling of $CO_2$ in an idealized experimental setup. If the current climate state was completely symmetric about the equator, no shift in the ITCZ is expected with increasing $CO_2$, as the radiative forcing and feedback would preserve the hemispheric symmetry. Hence, we consider the effect of increased $CO_2$ on the ITCZ position with a hemispheric asymmetry in the reference climate state. We introduce the hemispheric asymmetry by prescribing a northward cross-equatorial ocean transport in the aquaplanet slab ocean, thereby creating a warmer NH and the ITCZ to the north of the equator, as in the Earth's current climate. Then, the reference climate with a warmer NH is perturbed by a $CO_2$ doubling. The same set of experiments is performed with AM2 (with five different convection scheme parameters), AM3, HiRAM, and CAM5 to examine the robustness of the result.

As the NH is warmer in the reference state, the positive water vapor feedback causes the NH to warm more than the SH on average in response to a $CO_2$ doubling. However, the sign of north minus south tropical SST

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response relative to the reference ITCZ location varies between the models. Half of the models exhibit more warming on the northern flank of the reference ITCZ, whereas the other half exhibits more warming on the southern flank. Nevertheless, the ITCZ shifts northward in all models except one, which has a slight southward shift. In many of previous studies, the tropical precipitation shift has been understood based on the atmospheric energy budget. A key assumption was that the total gross moist stability ($\Delta m$), which is the total moist static energy transport per unit mass transport, stays constant. Then, the changes in the mass transport could only arise from changes in the cross-equatorial atmospheric energy transport or the divergence of equatorial energy input to the atmosphere. However, our study reveals that when accounting for the response to a nearly uniform $CO_2$ radiative forcing, the changes in $\Delta m$ cannot be neglected [see also, *Chou et al.*, 2013; *Merlis et al.*, 2013b; *Hill et al.*, 2015; *Feldl and Bordoni*, 2016]. The changes in $\Delta m$ are in fact dominant over the changes in the mass transport in determining changes in the atmospheric energy transport ($\delta F_A$). For instance, in the limiting case with no change in the mean circulation mass transport, the changes in $\Delta m$ can lead to the changes in $F_A$. Then, despite $\delta F_A \neq 0$, there will be no or little, if any, ITCZ shift. In the other limiting case of $\delta F_A = 0$, if changes in $\Delta m$ are large, there must be substantial changes in the mass transport, which will be accompanied by a shift in the tropical precipitation. However, previous studies in which $\delta\Delta m$ is neglected will predict no change in the mass transport when $\delta F_A = 0$. Hence, the shift of the energy flux equator, which is the latitude at which $F_A$ vanishes, is not always a good indicator for the ITCZ shift.

In many previous studies [*Kang et al.*, 2008; *Donohoe et al.*, 2013, 2014; *McGee et al.*, 2014; *Voigt et al.*, 2014], the shift of the energy flux equator has been successfully used to infer the ITCZ shift. When the climate response to the hemispherically asymmetric thermal forcing, such as cross-equatorial ocean heat transport or surface albedo change in one hemisphere, is considered, a substantial shift of the Hadley circulation is provoked. In comprehensive models, even a uniform radiative forcing can cause a significant shift of the Hadley circulation [*Frierson and Hwang*, 2012; *Donohoe et al.*, 2013], because the hemispheric asymmetry in the mean state can be enhanced due to the hemispheric differences in sea ice distribution that amplifies the warming response over the Arctic [e.g., *Screen and Simmonds*, 2010] and those in land-sea distribution that amplifies the NH warming relative to the SH [*Kamae et al.*, 2014]. In this regime, the response of the cross-equatorial atmospheric energy transport is directly related to the changes in the mass transport and accounts for the ITCZ shift. In contrast, in our idealized climate state, doubling $CO_2$ induces a rather subtle shift of the Hadley circulation. Then, the effect of the changes in the mass transport resulting from the shift of the Hadley circulation is much less important than the effect of $\delta\Delta m$ for inducing changes in the atmospheric energy transport. Therefore, the present study addresses the importance of accounting for the changes in the total gross moist stability in order to properly understand the response of tropical precipitation to the nearly uniform $CO_2$ radiative forcing. There are, however, large uncertainties in $\delta\Delta m$ as the vertical structure of moist static energy is affected by convection and clouds in subtle and, as our results demonstrate, parameterization-dependent ways. Thus, not only from the local physics point of view but also from the large-scale dynamics point of view, improving convection schemes and cloud modeling is a necessary step toward a more precise projection of tropical precipitation.

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