

Energetic Constraints on the Width of the Intertropical Convergence Zone

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ABSTRACT

The intertropical convergence zone (ITCZ) has been the focus of considerable research in recent years, with much of this work concerned with how the latitude of maximum tropical precipitation responds to natural climate variability and to radiative forcing. The width of the ITCZ, however, has received little attention despite its importance for regional climate and for understanding the general circulation of the atmosphere. This paper investigates the ITCZ width in simulations with an idealized general circulation model over a wide range of climates. The ITCZ, defined as the tropical region where there is time-mean ascent, displays rich behavior as the climate varies, widening with warming in cool climates, narrowing in temperate climates, and maintaining a relatively constant width in hot climates. The mass and energy budgets of the Hadley circulation are used to derive expressions for the area of the ITCZ relative to the area of the neighboring descent region, and for the sensitivity of the ITCZ area to changes in climate. The ITCZ width depends primarily on four quantities: the net energy input to the tropical atmosphere, the advection of moist static energy by the Hadley circulation, the transport of moist static energy by transient eddies, and the gross moist stability. Different processes are important for the ITCZ width in different climates, with changes in gross moist stability generally having a weak influence relative to the other processes. The results are likely to be useful for analyzing the ITCZ width in complex climate models and for understanding past and future climate change in the tropics.

1. Introduction

The intertropical convergence zone (ITCZ) is a band of intense rainfall at the ascending branch of the Hadley circulation, which is centered a few degrees north of the equator in the annual mean (Gruber 1972). The atmospheric and oceanic processes determining the annual-mean latitude of the ITCZ, and the sensitivity of this latitude to changes in climate, have been the focus of considerable research (e.g., Philander et al. 1996; Broccoli et al. 2006; Kang et al. 2008; Frierson et al. 2013; Marshall et al. 2014; Bischoff and Schneider 2014; Schneider et al. 2014), with paleoclimate data suggesting large migrations of the ITCZ between eras (Haug et al. 2001). However, the meridional extent (or width) of the ITCZ has received little attention, despite its

importance for interpreting paleoclimate records, for the dynamics of equatorial waves (Dias and Pauluis 2011), for the impacts of climate change, and for our understanding of the general circulation of the atmosphere.

The ITCZ width, as measured using a metric derived from satellite observations of brightness temperature, is approximately 7° of latitude in the time and zonal mean (Dias and Pauluis 2011) and is small compared to the width of the tropics (approximately 55°–70° latitude, depending on the definition used; Seidel et al. 2008). The ITCZ width varies zonally and seasonally, with, for example, a wide ITCZ over the Indian Ocean and a narrow ITCZ over the Atlantic Ocean (Fig. 1) and a generally wider ITCZ between May and October when the ITCZ is in the Northern Hemisphere (Dias and Pauluis 2011). Interannual variability affects not only the ITCZ position (Dai and Wigley 2000) but also the ITCZ width, with an observed widening in response to El Niño events (Dias and Pauluis 2011).

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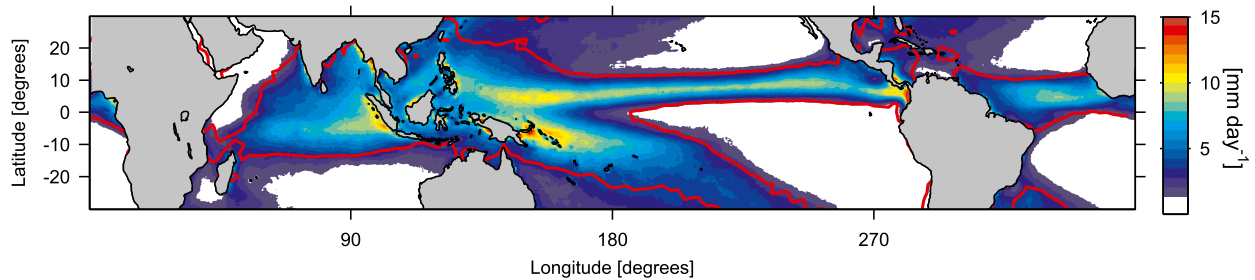


FIG. 1. Colors: Climatology of the annual-mean precipitation rate (1998–2014) over oceans from the Tropical Rainfall Measuring Mission (Liu et al. 2012). Red line: Zero contour of the 700-hPa annual-mean vertical velocity (1998–2014) over oceans from the ERA-Interim reanalysis (Dee et al. 2011).

The ITCZ width, or the ratio of the ITCZ area to the tropical descent area, is of fundamental importance for the regulation of the tropical climate, with longwave radiative cooling from the dry “radiator fin” regions, and consequently tropical sea surface temperatures (SSTs), highly dependent on this ratio (Pierrehumbert 1995). Consequently, model biases in ITCZ width could have implications for estimated climate sensitivity, like the double-ITCZ biases that have already been shown to be related to climate sensitivity (Tian 2015). Despite its importance, the mechanisms responsible for setting the ITCZ width and for its sensitivity to the seasonal cycle, to interannual variability, and to changes in climate have not been elucidated. In particular, the response of the ITCZ width to global warming has received little attention, in contrast to the observed and projected widening of the tropics as a whole (Lu et al. 2007; Hu and Fu 2007; Polvani et al. 2011; Adam et al. 2014; Levine and Schneider 2015).

While mechanisms controlling the ITCZ width have received limited attention, studies examining the processes determining the area fraction of deep convection have potential relevance for the ITCZ width. Bjerknes (1938) used simple thermodynamic arguments to show that moist convection favors an updraft region that is small relative to the downdraft region, although he considered only temperature tendencies due to vertical adiabatic motions (neglecting, for example, radiative cooling). Bretherton and Sobel (2002) derived a semi-analytical model of the Walker circulation to understand how the fraction of a given domain undergoing deep convection depends on the SST gradient. They found that the ratio of the area of deep convection to the total domain area depends not only on the SST gradient, but also on the gross moist stability (GMS), cloud–radiative feedbacks, and, in a follow-up study, atmosphere–ocean coupling (Sobel 2003). In addition, the “upped-ante mechanism” (Chou and Neelin 2004; Chou et al. 2009), associated with advection of anomalously dry air from

nonconvecting to convecting regions, is associated with reduced precipitation on the margins of convective zones and implies a narrowing of the ITCZ with warming.

Studies with a range of idealized climate models have noted a dependency of ITCZ width on the model’s dynamical core and resolution (Landu et al. 2014), on the reference relative humidity profile used in some parameterizations of convection (Kang et al. 2009), on the horizontal diffusion of moisture (Sobel and Neelin 2006), and on the radiative effects of clouds and water vapor (Voigt and Shaw 2015; Harrop and Hartmann 2016). A narrowing of the ITCZ in response to global warming in full-complexity climate model simulations has also been noted (Lau and Kim 2015). However, a comprehensive physical understanding of these sensitivities of the ITCZ width is lacking.

Here, we investigate the ITCZ width over a wide range of climates using an idealized general circulation model (GCM), focusing on the mechanisms controlling the time- and zonal-mean ITCZ width and the processes contributing to changes in width. We begin by defining our metric of ITCZ width (section 2) and deriving a theoretical scaling for the ITCZ width (section 3). The idealized GCM and the simulations are described (section 4) before the results and physical mechanisms are discussed (section 5). We conclude by summarizing our results and discussing directions for future research (section 6).

2. Definition of ITCZ width

No standard definition of ITCZ width exists in the literature. Dias and Pauluis (2011) estimate the ITCZ width by measuring the cross-equatorial meridional distance between latitudes where brightness temperature is equal to a specified threshold value (the ITCZ is largely covered by high clouds and thus coincides with low brightness temperatures). However, this definition of ITCZ width is sensitive to the specified brightness

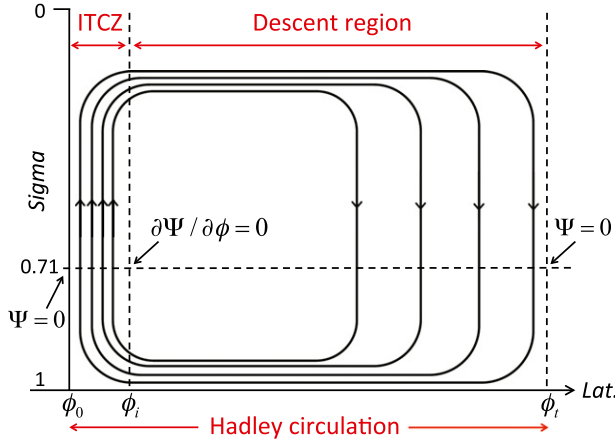


FIG. 2. Schematic diagram of the Hadley circulation with the boundaries of the ITCZ and the descent region indicated (following the definitions in section 2).

temperature threshold and is not clearly related to physical constraints, such as the energy, mass, or moisture balances of the atmosphere.

We introduce an alternative definition of ITCZ width based on the pressure velocity, ω . In this definition, the edge of the ITCZ is the latitude separating the region of time-mean ascent from the region of time-mean descent. Defined in this way, the ITCZ is the equatorial region where there is low-level mass convergence. The vertical velocity is proportional to the meridional gradient of the Eulerian-mean streamfunction (e.g., Peixóto and Oort 1984) and so we define the ITCZ width as the meridional distance between the latitude of the ascending branch of the Hadley circulation, ϕ_0 , where the streamfunction in the lower troposphere is zero, and the first latitude, ϕ_i , poleward of ϕ_0 , where the absolute value of the streamfunction has a local maximum (Fig. 2).¹ As we will show in the next section, this definition allows us to derive a scaling for the ITCZ width from the mass and energy balances of the tropical atmosphere.

The edge of the descent region, considered here to be the poleward boundary of the Hadley circulation, is defined as the closest latitude poleward of the ITCZ where the streamfunction is zero and is denoted ϕ_t (Fig. 2). This definition is consistent with an established

definition of the edge of the Hadley circulation (e.g., Lu et al. 2007) although other definitions exist (e.g., the edge of the Hadley circulation is sometimes defined as the latitude at which the zonal-mean surface winds transition from easterlies to westerlies). For convenience, we will generally discuss the ITCZ area, rather than the ITCZ width; the ITCZ area is given by $A_i = 2\pi R^2(\sin\phi_i - \sin\phi_0)$, and the area of the descent region is given by $A_d = 2\pi R^2(\sin\phi_t - \sin\phi_i)$, where R is the planetary radius.

Earth's annual- and zonal-mean ITCZ width, calculated using the definition described above and with 700-hPa vertical velocities (1998–2014) from the ERA-Interim reanalysis (Dee et al. 2011) (see the red contour in Fig. 1), is 27° of latitude. This is considerably wider than the 7° of latitude calculated by Dias and Pauluis (2011) using observations of brightness temperature, but the zonal variations of the ITCZ width as defined above in terms of the vertical velocity are substantial (Fig. 1).

3. Theory

Atmospheric mass and energy balance

To understand the physical processes determining the ITCZ area, we derive a scaling from the mass and moist static energy balances of the atmosphere. The steady-state mass balance of the Hadley circulation can be written in terms of bulk pressure velocities in the ITCZ and descent regions, defined respectively as

$$\begin{aligned}\tilde{\omega}_i &\equiv \frac{\Psi(\sigma_L, \phi_0) - \Psi(\sigma_L, \phi_i)}{A_i} = \frac{-\Psi(\sigma_L, \phi_i)}{A_i}, \\ \tilde{\omega}_d &\equiv \frac{\Psi(\sigma_L, \phi_i) - \Psi(\sigma_L, \phi_t)}{A_d} = \frac{\Psi(\sigma_L, \phi_i)}{A_d},\end{aligned}\quad (1)$$

where Ψ is the Eulerian-mean streamfunction. From (1), the mass balance for the Hadley circulation can be written as

$$A_i \tilde{\omega}_i = -A_d \tilde{\omega}_d. \quad (2)$$

In steady state, and neglecting the kinetic energy of the atmosphere, the vertically integrated zonal-mean energy budget of the atmosphere can be written approximately as (e.g., Bischoff and Schneider 2014)

$$\bar{S} - \bar{L} - \bar{O} = \nabla \cdot \{\bar{v}h\}, \quad (3)$$

where S and L are the net top-of-atmosphere (TOA) shortwave and longwave radiative fluxes, respectively, O is the ocean heat uptake, v is the meridional velocity, $h = c_p T + Lq + gz$ is the moist static energy (MSE), $\{\cdot\}$

¹ To determine the width of the ITCZ, we analyze the streamfunction at $\sigma_L = p_L/p_s = 0.71$, where p_s is the surface pressure. In our definition of the ITCZ width we are considering the hemispherically symmetric case. This definition can be generalized and applied to hemispherically asymmetric situations by instead defining the ITCZ width to be the meridional distance between the latitudes north and south of ϕ_0 (and closest to ϕ_0) where the magnitude of the streamfunction has local maxima.

denotes a mass-weighted vertical integral over the atmosphere, and $\overline{(\cdot)}$ denotes a time-mean quantity.² Following Neelin and Held (1987), assuming that $\omega = 0$ at the surface (i.e., neglecting topography) and taking an area average over a latitude band, the atmospheric energy balance (3) can be written as

$$\begin{aligned} \langle \bar{S} - \bar{L} - \bar{O} \rangle &= -\Delta h \bar{\omega}/g + \langle \{\bar{v} \cdot \nabla \bar{h}\} \rangle + \langle \{\nabla \cdot \bar{v} \bar{h}'\} \rangle, \\ \Rightarrow \bar{\omega} &= -\frac{g}{\Delta h} \langle \bar{S} - \bar{L} - \bar{O} - \{\bar{v} \cdot \nabla \bar{h}\} - \{\nabla \cdot \bar{v} \bar{h}'\} \rangle, \end{aligned} \quad (4)$$

where

$$\Delta h = -\frac{\langle \bar{h}(\nabla \cdot \bar{v}) \rangle}{\bar{\omega}/g} \quad (6)$$

is the GMS defined in terms of the bulk pressure velocity,³ $\langle \cdot \rangle$ denotes a meridional average over a latitude band, and primes denote departures from time means. The GMS, as defined above, is the MSE transport by the divergent mean flow normalized by the mass-flux divergence integrated over the lower troposphere [an alternative definition of the GMS is the ratio of the MSE flux to the mass flux (e.g., Frierson 2007; Kang et al. 2009)].

Combining (2) with the atmospheric MSE balance (4) averaged over the ITCZ and the descent region separately yields

$$\frac{A_i}{A_d} = -\frac{\bar{\omega}_d}{\bar{\omega}_i} = -\frac{\langle \bar{S} - \bar{L} - \bar{O} - \{\bar{v} \cdot \nabla \bar{h}\} - \{\nabla \cdot \bar{v} \bar{h}'\} \rangle_d}{\langle \bar{S} - \bar{L} - \bar{O} - \{\bar{v} \cdot \nabla \bar{h}\} - \{\nabla \cdot \bar{v} \bar{h}'\} \rangle_i} \frac{\Delta h_i}{\Delta h_d}, \quad (7)$$

where $\langle \cdot \rangle_i$ and $\langle \cdot \rangle_d$ denote area averages over the ITCZ and descent regions, respectively. The GMS in the ITCZ is denoted as Δh_i , with the GMS in the descent region denoted as Δh_d . The ratio of the ITCZ width to the width of the descent region is proportional to the ratio of the GMS in both regions, and it further depends on the respective net energy inputs ($\bar{S} - \bar{L} - \bar{O}$), the advection of MSE by the mean (Hadley) circulation, and the divergence of the transient-eddy MSE flux in each region. Consistent with previous theoretical work (Bretherton

and Sobel 2002; Chou and Neelin 2004), the relation (7) suggests a narrow ITCZ relative to the descent region when the GMS in the ITCZ is small. The GMS is generally larger in the subtropics than in the ITCZ (e.g., Hill et al. 2015) and so, if all other quantities in (7) were equal in the ITCZ and descent region, we would expect the descent region to be larger than the ITCZ (i.e., $A_d > A_i$).⁴

An expression for fractional changes in ITCZ area relative to fractional changes in the descent area is obtained by linearizing (7) and rearranging:

$$\begin{aligned} \frac{\delta A_i}{A_i} - \frac{\delta A_d}{A_d} &= \underbrace{\frac{\delta(\Delta h_i)}{\Delta h_i} - \frac{\delta(\Delta h_d)}{\Delta h_d}}_{\delta \text{GMS}} \\ &+ \underbrace{\frac{1}{H_i} \left[\delta \langle \bar{S} - \bar{L} - \bar{O} \rangle_d \frac{H_i}{H_d} - \delta \langle \bar{S} - \bar{L} - \bar{O} \rangle_i \right]}_{\delta \text{NEI}} \\ &- \underbrace{\frac{1}{H_i} \left[\delta \langle \{\bar{v} \cdot \nabla \bar{h}\} \rangle_d \frac{H_i}{H_d} - \delta \langle \{\bar{v} \cdot \nabla \bar{h}\} \rangle_i \right]}_{\delta \text{MeanAdv}} \\ &- \underbrace{\frac{1}{H_i} \left[\delta \langle \{\nabla \cdot \bar{v} \bar{h}'\} \rangle_d \frac{H_i}{H_d} - \delta \langle \{\nabla \cdot \bar{v} \bar{h}'\} \rangle_i \right]}_{\delta \text{Eddy}}, \end{aligned} \quad (8)$$

where $H_i = \langle \{\bar{h}(\nabla \cdot \bar{v})\} \rangle_i = -\Delta h_i \bar{\omega}_i/g$ and $H_d = \langle \{\bar{h}(\nabla \cdot \bar{v})\} \rangle_d = -\Delta h_d \bar{\omega}_d/g$ are the components of the vertically integrated divergence of MSE associated with mass-flux divergence, averaged over the ITCZ and the descent region, respectively. Equation (8) reveals that changes in GMS, in the net energy input (NEI) to the atmosphere, in MSE divergence by transient eddies, and in MSE advection by the Hadley circulation have the potential to contribute to fractional changes in the ITCZ area. In the next section, we will discuss simulated changes in the ITCZ over a wide range of climates and the physical processes contributing to these changes.

4. Idealized GCM

We perform simulations using the moist idealized GCM described by O'Gorman and Schneider (2008),

² The energy storage term for the atmosphere, omitted from (3), is found to be negligible for the simulations and averaging periods employed in this paper (see section 4 for details about the GCM and the simulations performed).

³ In practice, we calculate the GMS by inverting (4) to solve for Δh , rather than using the explicit Eq. (6). The two methods for estimating the GMS give qualitatively similar results but quantitative differences arise because of discretization errors associated with computing the gradient and divergence operators.

⁴ In very cold climates, the atmosphere cannot hold much water vapor and is effectively dry, so that the total MSE transport is dominated by sensible heat transport. Invoking weak temperature gradients in the tropical free troposphere (e.g., Sobel and Bretherton 2000) and assuming a small meridional MSE gradient in the lower troposphere in the absence of moisture, we might expect the GMS to be similar in the ITCZ and descent regions. In this cold limit, and assuming no difference in all other quantities in (7) between the ITCZ and descent region, we would expect the areas of the ITCZ and descent region to be of comparable size, $A_i \approx A_d$.

which is similar to that of Frierson et al. (2006) and Frierson (2007). The Robert–Asselin filter for leapfrog time stepping has been replaced with the improved Robert–Asselin–Williams filter (Williams 2011), but in all other respects the model used here is as described by O’Gorman and Schneider (2008). We run the GCM at a horizontal spectral resolution of T127 (corresponding to approximately 1° resolution in latitude) with 20 vertical sigma levels and an integration time step of 150 s. The model is configured as an aquaplanet with a slab ocean of uniform heat capacity equivalent to 1 m of liquid water. No horizontal heat transfer is permitted below the surface, meaning that when the model is in equilibrium there is no ocean heat uptake or release.

The top-of-atmosphere insolation is specified as a representation of the annual-mean profile, and there are neither seasonal nor diurnal cycles. Shortwave radiative fluxes in the atmosphere are specified as a function of latitude and pressure, and longwave fluxes are computed using a two-stream gray radiation scheme. The climate is varied by changing the longwave optical thickness, which is analogous to varying the atmospheric concentrations of longwave absorbers such as water vapor and CO_2 . The longwave optical depth is defined as $\tau = \alpha \tau_{\text{ref}}$, where τ_{ref} is a reference longwave optical thickness profile specified as a function of latitude and pressure, and the parameter α is varied from 0.4 to 6.0.⁵ The simulation with $\alpha = 1.0$ corresponds to an Earth-like climate, with a global-mean surface air temperature of 286 K. The coldest and warmest simulations have global-mean surface air temperatures of 269 and 315 K, respectively. Radiative feedbacks associated with clouds and water vapor are not included in this version of the model. Simulations are spun up for 700 days, and all quantities are averaged over the subsequent 1000 days. Analogous simulations, performed using this idealized GCM, have been discussed in previous studies (e.g., O’Gorman and Schneider 2008; Merlis and Schneider 2011; Byrne and O’Gorman 2013).

5. Results

a. ITCZ area in simulations

The ITCZ area, defined in terms of the mass streamfunction as described in section 2, is a nonmonotonic function of global-mean surface air temperature (Figs. 3, 4a, and 5) and is small compared to the area of the

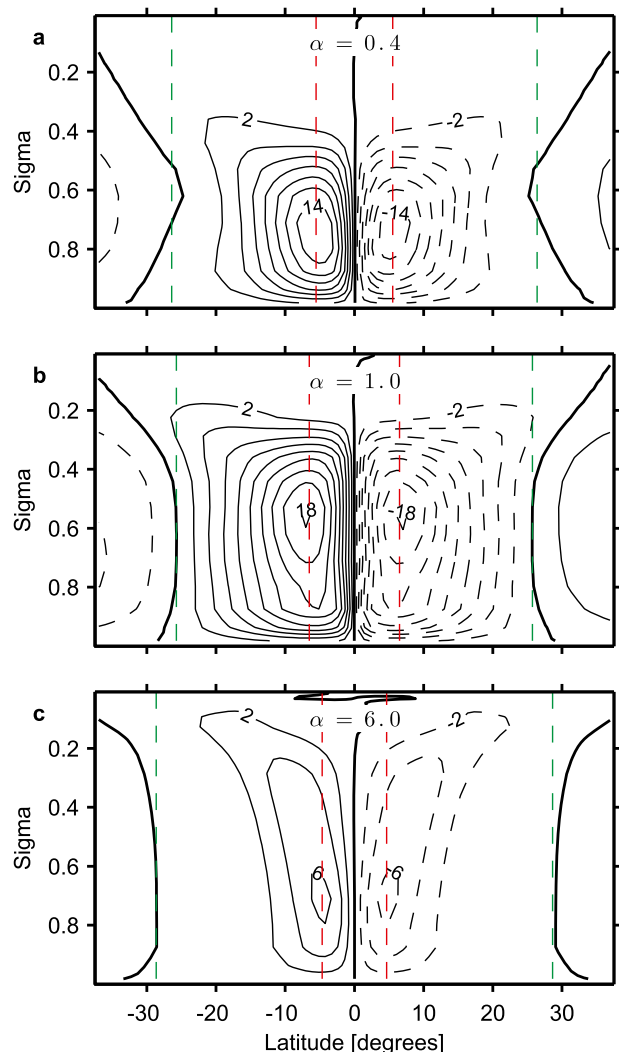


FIG. 3. Eulerian-mean streamfunction (time- and zonal-average) for (a) a cold simulation ($\alpha = 0.4$), (b) the reference simulation with a climate similar to that of the present-day Earth ($\alpha = 1.0$), and (c) a hot simulation ($\alpha = 6.0$). The contour interval is $2 \times 10^{10} \text{ kg s}^{-1}$. Dashed black lines denote negative streamfunction values and thick solid black lines denote the zero contours. The red and green dashed lines show the edges of the ITCZ and the descent region, respectively.

Hadley circulation (Fig. 3). Averaged over all simulations, the ITCZ area is 21% of the total area of the Hadley circulation. In the coldest climate ($\alpha = 0.4$), the ITCZ width is 11.0° and increases with temperature to a maximum width of 13.1° for a climate similar to that of present-day Earth ($\alpha = 1.0$). The ITCZ narrows with increasing temperature in yet warmer climates, attaining a minimum width of 9.1° at $\alpha = 2.5$ and staying approximately constant in very hot climates. The area of the descent region is anticorrelated with the ITCZ area (Figs. 5 and 6), such that when the ITCZ narrows the

⁵ Fifteen simulations are performed, each with a different longwave optical thickness profile specified by $\tau = \alpha \tau_{\text{ref}}$, where $\alpha = 0.4, 0.5, 0.7, 0.8, 1.0, 1.2, 1.5, 1.8, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0$.

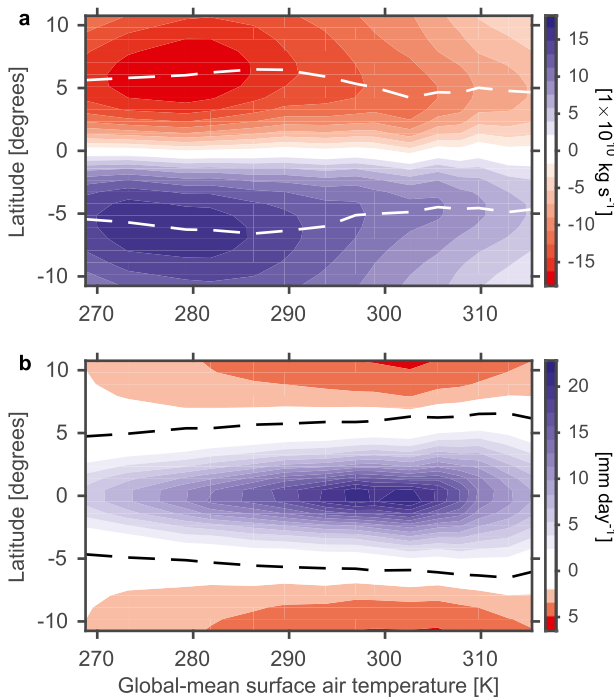


FIG. 4. (a) Mass streamfunction at $\sigma_L = 0.71$ and (b) precipitation minus evaporation in the tropics, with both quantities plotted as a function of latitude and global-mean surface air temperature for the 15 idealized GCM simulations. The white dashed lines indicate the boundaries of the ITCZ defined in terms of the mass streamfunction (the “mass ITCZ”), and the black dashed lines indicate the boundaries of the ITCZ defined in terms of the zero line of precipitation minus evaporation (the “moisture ITCZ”).

descent area tends to widen. The magnitude of the fractional changes in ITCZ area is generally larger than that of the changes in the area of descent (Fig. 6). Opposite-signed changes in the ITCZ and descent areas are consistent with fractional changes in the area of the Hadley circulation being smaller in magnitude than either the fractional changes in ITCZ area or in the descent region area (Fig. 6).

An ITCZ defined in terms of atmospheric moisture convergence (i.e., the tropical region where time-mean precipitation minus evaporation is positive) has a similar width to the ITCZ defined in terms of the mass streamfunction (cf. Fig. 4a and 4b), although the two quantities scale somewhat differently with climate. The relationship between these two definitions of the ITCZ is investigated later in this section.

b. Processes controlling the ITCZ area

The physical processes controlling the ITCZ area are investigated using expression (8) derived from the mass and MSE balances of the Hadley circulation. The expression successfully captures the simulated changes in ITCZ area in cold, temperate, and hot climates (Fig. 6),

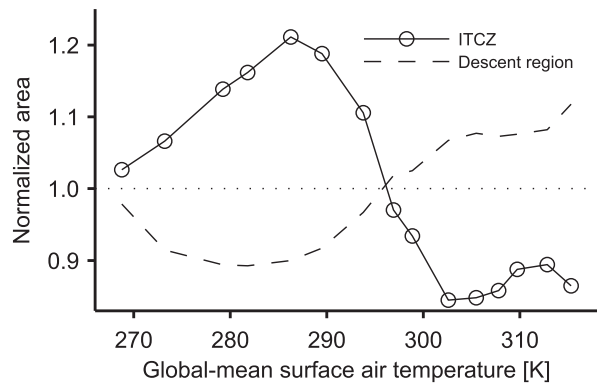


FIG. 5. Area of the ITCZ normalized by the ITCZ area averaged over all simulations (solid line), and descent region area normalized by the mean descent region area (dashed line) vs global-mean surface air temperature. Each dot represents a different simulation.

but not the changes in warm climates where the GMS passes through zero in both the ITCZ and descent region and the Hadley circulation becomes thermally indirect, with negative GMS (Fig. 7a).

Using (8), we can decompose changes in ITCZ area into components due to fractional changes in GMS (δGMS), changes in the net energy input to the atmosphere (δNEI), changes in mean advection ($\delta\text{MeanAdv}$), changes in the MSE divergence by transient eddies (δEddy), and fractional changes in the descent area ($\delta A_d/A_d$).

1) GROSS MOIST STABILITY COMPONENT, δGMS

Changes in GMS contribute to the ITCZ widening tendency in cooler climates and to a narrowing tendency in temperate climates (Fig. 8a). The sign of the changes in ITCZ area due to changes in GMS depends on the relative fractional changes in GMS in the ITCZ and the descent region [see (8)]. In cool climates, the GMS increases with warming in both regions (not shown) but larger fractional increases occur in the ITCZ (where GMS is substantially smaller than in the descent region). This results in a mean widening tendency of $2.6\% \text{ K}^{-1}$ over all simulations.

For climates with a global-mean surface-air temperature greater than approximately 287 K, the GMS decreases with warming in both the ITCZ and the descent region, contrary to theoretical predictions (Hill et al. 2015). Fractional decreases in the GMS in the ITCZ dominate those in the descent region to give a narrowing tendency. As the climate warms further, the GMS in both the ITCZ and the descent region becomes small and then changes sign so that the Hadley circulation becomes thermally indirect, importing energy from the descent region to the ITCZ. Interestingly, reanalyses

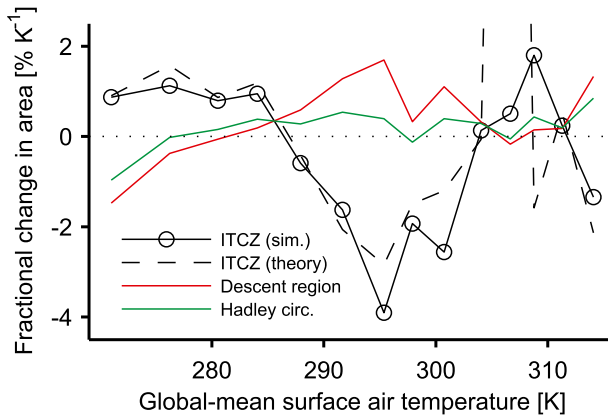


FIG. 6. Fractional changes in the simulated areas of the ITCZ (solid black line), the descent region (solid red line), and the Hadley circulation (solid green line) between pairs of simulations, as a function of the midpoint global-mean surface air temperature for each pair. The dashed line shows the changes in the fractional area of the ITCZ estimated using (8).

suggest that the ITCZ in the eastern Pacific has a negative GMS in the annual mean (Back and Bretherton 2006; Peters et al. 2008), although there is considerable uncertainty due to the sparsity of data in this region (e.g., Raymond et al. 2009). Although the validity of the expression for the ITCZ area (8) is not dependent on a thermally direct Hadley circulation, a consequence of the GMS passing through zero is a noisy δGMS at high temperatures.

2) NET ENERGY INPUT COMPONENT, δNEI

The time-mean net energy input to the atmosphere, $\bar{S} - \bar{L} - \bar{O}$, increases with warming in both the ITCZ and the descent region in cool and moderate climates (Fig. 7b). In these idealized simulations, there is no change in atmospheric solar heating as climate is varied, and there is no ocean heat uptake at equilibrium ($\delta\bar{S} = 0$, $\bar{O} = 0$). Thus, an increase in net energy input to the tropical atmosphere means that the outgoing longwave radiation (OLR) is decreasing with warming despite increasing temperatures. This is a consequence of enhanced poleward MSE export with warming. Although cloud-radiative feedbacks are not included in our idealized GCM, they are likely to affect the net energy input to the atmosphere and consequently the area of deep convection and the ITCZ, as demonstrated for the Walker circulation by Bretherton and Sobel (2002).

Increases in net energy input to both the ITCZ and the descent region give a robust narrowing tendency for the ITCZ in cool and temperate climates (Fig. 8b). The ratio of the area-averaged mean divergent MSE transport in the ITCZ to that in the descent region, H_i/H_d , has a magnitude of approximately 2 in these simulations.

Consequently, a change in the net energy input to the descent region has a greater impact on the ITCZ area than an equal change in the net energy input to the ITCZ. In hot climates, the net energy inputs to the ITCZ and the descent region both decrease with warming (Fig. 7b), consistent with a reduction in MSE export out of the tropics by atmospheric motions [see also Caballero and Langen (2005)], resulting in a widening tendency for the ITCZ.

3) MEAN-ADVECTION COMPONENT, $\delta\text{MeanAdv}$

Advection of MSE by the Hadley circulation in the descent region has a substantial influence on the ITCZ area, widening the ITCZ with warming in cool climates and narrowing the ITCZ in temperate climates (Fig. 8c). This temperature dependence of the influence of mean MSE advection on the width of the ITCZ arises because the Hadley circulation strength is a nonmonotonic function of temperature (Figs. 3 and 9a). Although the near-surface MSE gradient in the descent region increases with warming for all climates (Fig. 9b), the low-level meridional velocity increases with warming in cool climates but decreases with warming in warm climates (Fig. 9a), causing the mean advection component of the MSE budget to peak at a temperature of approximately 290 K (Fig. 7c) and leading to $\delta\text{MeanAdv}$ having both widening and narrowing tendencies for the ITCZ.

Because of small meridional gradients of near-surface MSE in the ITCZ (Fig. 9b), the mean advection of MSE within the ITCZ is small (Fig. 7c) and has only a weak narrowing influence on the ITCZ area (Fig. 8c).

4) TRANSIENT-EDDY COMPONENT, δEddy

The strengthening divergence of MSE associated with transient eddies generally exerts a widening influence on the ITCZ as the climate warms (Fig. 8d). This widening tendency is in qualitative agreement with Sobel and Neelin (2006), who found that increasing the horizontal moisture diffusivity in an axisymmetric model (analogous to increasing the transient-eddy moisture flux) resulted in a wider ITCZ. Transient eddies have previously been shown to modulate the strength of the Hadley circulation through their effect on the both the angular momentum (Walker and Schneider 2006) and energy budgets (Singh and Kuang 2016) of the tropics, and are also important for the extent of the Hadley circulation (Korty and Schneider 2008; Levine and Schneider 2015). Although MSE divergence by transient eddies has been found to be an important term in the energy budgets of the eastern Pacific (Peters et al. 2008) and the ITCZ in an idealized model (Nolan et al. 2010), the quantitative relationship between transient eddies

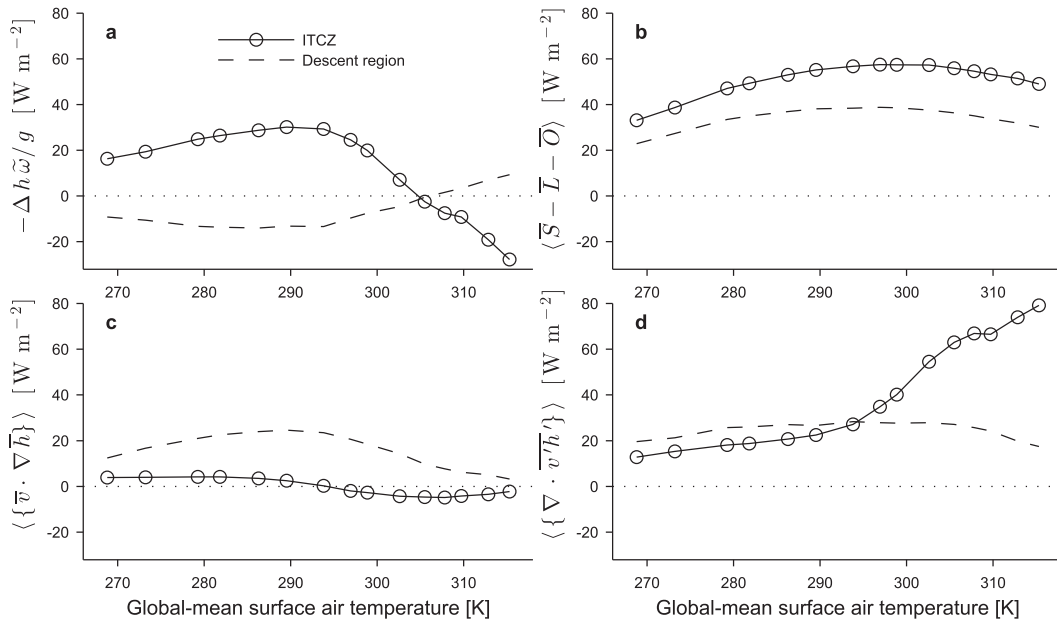


FIG. 7. Various terms in the vertically integrated atmospheric moist static energy budget (4) as a function of global-mean surface air temperature, averaged over the ITCZ (solid lines) and the descent region (dashed lines), respectively.

and the size of the ITCZ has not been demonstrated previously.

Strengthening MSE divergence by transient eddies in the ITCZ and in the descent region both contribute to a

widening of the ITCZ (Fig. 8d). In the ITCZ, the transient-eddy MSE divergence increases monotonically with warming (Fig. 7d), following closely the divergence of moisture and latent heat by the eddies

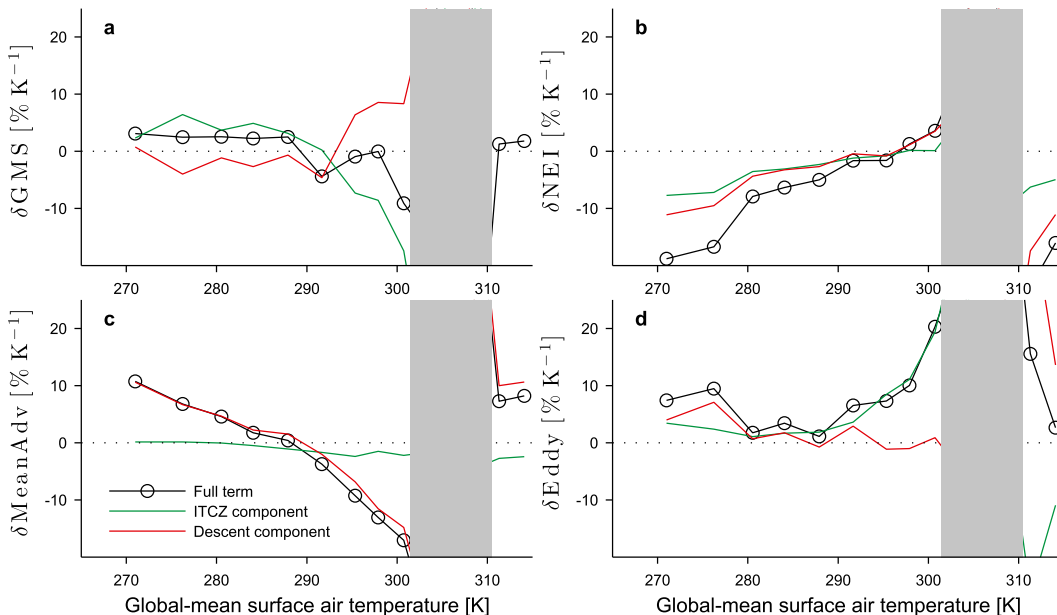


FIG. 8. Terms in the expression for changes in ITCZ area relative to the descent area (8). The full terms are shown (black lines) along with the components of each term due to changes in the various quantities in the ITCZ (green lines) and the descent region (red lines). Gray shading masks the temperatures for which each component is noisy due to small GMS values.

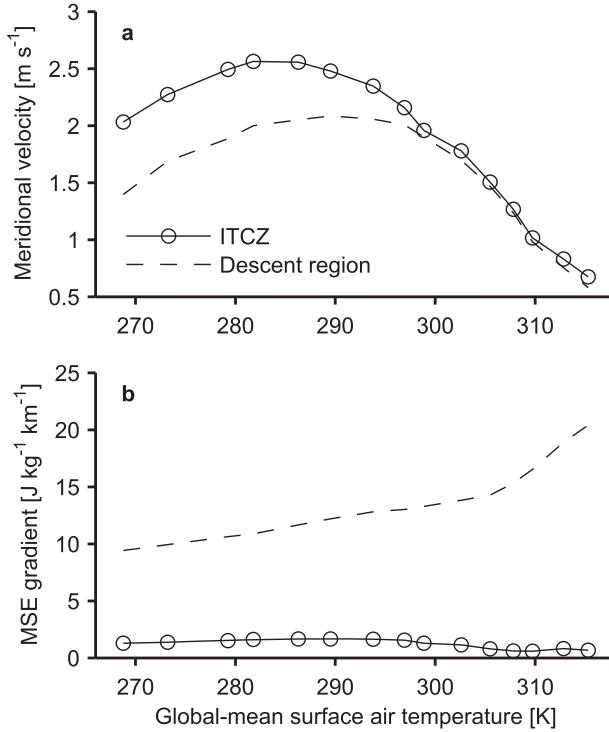


FIG. 9. Absolute (a) meridional surface-air velocity and (b) meridional gradient of surface-air moist static energy averaged over the ITCZ (solid lines) and the descent region (dashed lines).

(the divergence of dry static energy by transient eddies is negligible in the ITCZ). For the descent region, however, the transient-eddy MSE divergence is a non-monotonic function of temperature, increasing weakly with warming in cool climates, staying approximately constant in temperate and warm climates, and decreasing with warming in hot climates. The MSE divergence in the descent region is the difference between the meridional MSE flux at the edge of the Hadley circulation and the flux at the edge of the ITCZ. Thus, the variation with climate of the transient-eddy MSE divergence in the descent region depends on the relative changes in the MSE fluxes by transient eddies at the edges of the Hadley circulation and the ITCZ: in cool climates, the flux at the edge of the Hadley circulation increases more with warming than the flux at the edge of the ITCZ, leading to a widening tendency for the ITCZ; the opposite is the case in hot climates. Overall, the MSE fluxes at the edges of the ITCZ and Hadley circulation tend to change by similar magnitudes as the climate warms, consistent with the weak dependence of the MSE flux divergence by transient eddies in the descent region on temperature (Fig. 7d). The net effect of changes in transient eddies with warming is to widen the ITCZ, for all climates.

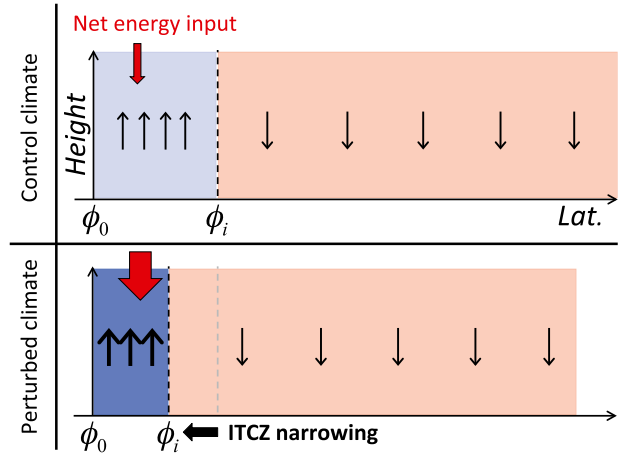


FIG. 10. Schematic diagram of the Hadley circulation illustrating the mechanism by which increases in net energy input to the ITCZ lead to a narrowing of the ITCZ relative to the descent region. The latitudes of the ascending branch and of the edge of the ITCZ are denoted by ϕ_0 and ϕ_i , respectively. The blue shading indicates the region where there is time-mean ascent (i.e., the ITCZ) and the red shading indicates the descent region; the darker the shading, the larger the magnitude of the vertical velocity in the given region.

5) FRACTIONAL CHANGES IN DESCENT AREA, $\delta A_d/A_d$

The fractional change in ITCZ area *relative* to the fractional change in the descent area is estimated by (8). Fractional changes in the area of the descent region are smaller in magnitude compared to fractional changes in ITCZ area, and are of opposite sign (Fig. 6). To use (8) to estimate the *absolute* change in the ITCZ area for a given change in climate, an additional constraint is needed, namely, a theory for the extent of the Hadley circulation. The processes controlling the extent of the Hadley circulation remain under debate (e.g., Levine and Schneider 2015); however, it is clear that the Hadley circulation terminus is strongly influenced by midlatitude baroclinic eddies. The extent of the Hadley circulation is not the focus of this paper. But it should be noted that an expansion of the Hadley circulation would lead to an expansion of the ITCZ even if the sum of the all the processes described above were zero (i.e., $\delta \text{GMS} + \delta \text{EnergyInput} + \delta \text{MeanAdv} + \delta \text{Eddy} = 0$).

c. Physical interpretation

A physical understanding of the relationship between changes in GMS, net energy input, mean advection of MSE, transient-eddy MSE transport, and the ITCZ width is relatively straightforward. For the subsequent discussions we will assume that the GMS in the ITCZ and the descent region is positive (i.e., the

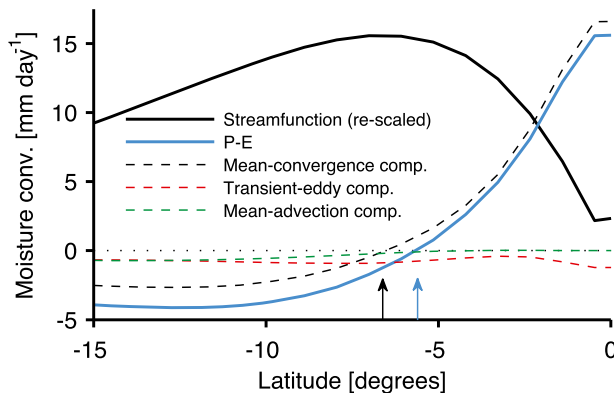


FIG. 11. Precipitation minus evaporation (blue solid line) along with the mean-convergence (black dashed line), transient-eddy (red dashed line), and mean-advection (green dashed line) components of the atmospheric moisture budget (9) for the reference simulation ($\alpha = 1.0$). The streamfunction at $\sigma_L = 0.71$ has also been plotted (black solid line), with its magnitude having been rescaled so that it matches the magnitudes of the moisture convergence terms. The black and blue arrows indicate the poleward boundaries of the mass ITCZ and the moisture ITCZ, respectively.

Hadley circulation is thermally direct). An increase in GMS in the ITCZ is equivalent to an increase in the efficiency of energy export by the Hadley circulation. Assuming all other terms in the energy budget of the ITCZ remain constant, an increase in GMS requires reduced vertical velocity in order to satisfy the energy budget of the ITCZ [see (5)]. From the mass budget of the Hadley circulation (2), a reduced vertical velocity in the ITCZ implies a widening of the ITCZ relative to the descent region in order for the same quantity of mass to be transported vertically in the ITCZ (assuming a fixed vertical velocity in the descent region).

The influence of net energy input to the atmosphere, mean advection of MSE, and transient-eddy MSE transport on the ITCZ width can be interpreted in a similar way to the influence of GMS. For example, an increase in the net energy input to the ITCZ via, for example, reduced OLR implies an enhanced vertical velocity in the ITCZ in order to export the excess energy, assuming as before that all other terms in the energy budget remain constant. From the mass budget, an increase in the vertical velocity leads to a narrowing of the ITCZ relative to the descent region (see schematic in Fig. 10).

In the descent region, an increase in the net energy input results in a reduction in the energy that the mean divergent flow (i.e., the Hadley circulation) is required to import in order to satisfy energy balance, and consequently a reduced vertical velocity. A reduced vertical velocity in the descent region implies a

narrowing of the ITCZ relative to the descent region. Thus, increases in net energy input to both the ITCZ and the descent region tend to narrow the ITCZ. By considering how changes in mean advection of MSE and in transient-eddy MSE transport affect the energy balances and vertical velocities in the ITCZ and the descent region, analogous arguments can be made for the influence of these processes on the ITCZ width.

As noted earlier, a change in net energy input to the descent region has a larger effect on the ITCZ width than an equal change in net energy input per unit area to the ITCZ. This relatively large sensitivity of the ITCZ width to energy budget perturbations in the descent region is due to the magnitude of the mean divergent MSE transport per unit area being larger in the ITCZ than in the descent region, that is, $|\Delta h_i \tilde{\omega}_i / g| > |\Delta h_d \tilde{\omega}_d / g|$ (see Fig. 7a). This implies that a larger fractional change in vertical velocity is needed in the descent region than in the ITCZ in order to balance a given change in net energy input per unit area, and thus the descent region has a larger effect on fractional changes in ITCZ width.

d. Relationship between mass and moisture ITCZs

We have defined the ITCZ as the tropical region where there is time-mean low-level mass convergence, and have analyzed the processes controlling the width of this region. As mentioned earlier, the ITCZ could alternatively be defined as the tropical region where there is time-mean moisture convergence. In steady state, moisture convergence by the atmosphere is balanced by precipitation minus evaporation, $P - E$, so that the moisture budget may be written as $P - E = -\nabla \cdot \{\bar{v}q\}$ (e.g., Byrne and O’Gorman 2015). Thus, the ITCZ defined in terms of moisture convergence is coincident with the tropical region where $P - E > 0$. For convenience, in the discussions below we will refer to these two definitions of the ITCZ as the “mass ITCZ” and the “moisture ITCZ,” respectively.

The mass and moisture ITCZs in our idealized simulations have similar sizes, with average widths of 10.8° and 11.6° of latitude, respectively (averaged over all simulations). The mass ITCZ is wider than the moisture ITCZ in cool climates, but the opposite is the case in warm climates (Fig. 4). The moisture ITCZ widens with warming for all except the warmest simulation (Fig. 4b), in contrast to the nonmonotonic dependence of the mass ITCZ on temperature (Fig. 4a).

To understand the contrasting widths of the mass and moisture ITCZs, we examine the steady-state zonal mean atmospheric moisture budget written in terms of a mean-convergence component, a mean-advection component, and a transient-eddy component:

$$P - E = \underbrace{-\{q\nabla \cdot \bar{v}\}}_{\text{Mean-conv. comp.}} + \underbrace{-\{\bar{v} \cdot \nabla \bar{q}\}}_{\text{Mean-adv. comp.}} - \underbrace{\{\nabla \cdot \bar{v}'q'\}}_{\text{Transient-eddy comp.}}. \quad (9)$$

For the reference simulation ($\alpha = 1.0$), $P - E$ near the equator is primarily balanced by the mean-convergence component of (9); that is, the moisture convergence associated with the convergent mean flow. The transient-eddy component adds a small contribution and the mean-advection component is negligible (Fig. 11). If both the transient-eddy and mean-advection components of the moisture budget were zero, then $P - E$ would be entirely balanced by the mean-convergence component. In such a scenario, the regions of low-level mass convergence and moisture convergence would coincide, as would the mass and moisture ITCZs (see the black dashed line and black arrow in Fig. 11). However, the moisture divergence associated with transient eddies is nonzero in our idealized simulations, even near the equator, resulting in a meridional shift in the zero latitude of $P - E$ and in the edge of the moisture ITCZ relative to the edge of the mass ITCZ (cf. the black and blue arrows in Fig. 11). The mean-advection component of the moisture budget has only a minor influence on the width of the moisture ITCZ in the reference simulation (Fig. 11). Thus, although the width of the moisture ITCZ depends primarily on the low-level mass convergence and, consequently, the width of the mass ITCZ, the magnitude and meridional structure of the transient-eddy moisture divergence in the tropics and, to a lesser extent, the advection of moisture by the Hadley circulation, lead to small differences in the widths of the mass and moisture ITCZs and to qualitative differences in how these quantities scale with climate (Figs. 4a and 4b). It should be noted, however, that the importance of transient-eddy moisture fluxes near the equator may be exaggerated in our idealized simulations, although it is clear eddy moisture fluxes penetrate to the equator also in Earth's atmosphere (Schneider et al. 2006; Couhert et al. 2010).

6. Summary and discussion

Based on the mass and energy budgets of the Hadley circulation, we have derived an expression for the ratio of the ITCZ area to the area of the descent region, with the boundaries of the ITCZ and the descent region defined in terms of the mass streamfunction. The size of the ITCZ, relative to the descent region, is found to depend on four quantities: the net energy input to the atmosphere, the MSE divergence by transient eddies, the GMS, and the advection of MSE by the Hadley circulation. Fractional changes in the area of the ITCZ (relative to fractional changes in the descent region area)

are expressed in terms of changes in these quantities, and the resulting scaling is applied to idealized GCM simulations to investigate the physical processes contributing to changes in the ITCZ area over a wide range of climates.

The simulated ITCZ displays rich behavior as the climate is varied: the ITCZ widens with warming in cool climates, narrows in temperate climates, and maintains an approximately constant area in hot climates. Fractional changes in the area of the descent region are generally smaller in magnitude and are anticorrelated with changes in ITCZ area (i.e., when the ITCZ widens, the descent region tends to narrow). Consequently, fractional changes in the extent of the Hadley circulation (a topic that has received considerable attention in recent years) are small compared to fractional changes in the area of either the ITCZ or the descent region. The variation of the ITCZ area with warming in the idealized simulations is captured by the scaling (8) in cool, temperate, and hot climates, but not in warm climates where the expression is ill behaved due to the GMS in both the ITCZ and the descent region becoming small and passing through zero.

Changes in atmospheric net energy input, advection of MSE by the Hadley circulation, and transient-eddy MSE divergence influence the ITCZ area strongly, with changes in GMS having a weaker effect. Increasing net energy input to the tropical atmosphere with warming (due to strengthened MSE export and decreased OLR) tends to narrow the ITCZ in cool and temperate climates, and decreasing energy input with warming (consistent with a reduced poleward MSE flux) in warm and hot climates widens the ITCZ. The mean advection term, similarly, influences the ITCZ area differently in different climates, with a widening tendency in cool climates and a narrowing tendency in warmer climates. The nonmonotonicity of the mean advection term is due to the Hadley circulation strength, which itself is a nonmonotonic function of temperature in these idealized simulations. The transient-eddy term widens the ITCZ with warming in all climates, largely because of increases in the poleward flux of MSE by the eddies.

Our analysis highlights that to understand the time-mean ITCZ width, mechanisms beyond the vertical adiabatic motions considered by Bjerknes (1938) need to be invoked. Several of the processes identified here as being important for the ITCZ width, such as changes in GMS and radiative feedbacks, have been shown by Bretherton and Sobel (2002) to influence the fraction of the Walker circulation undergoing deep convection. In addition, we have elucidated the critical role played by transient eddies in controlling the ITCZ width. We have also discussed the relationship between ITCZ widths

defined in terms of mass convergence versus moisture convergence, highlighting that differences between the two metrics are modulated by the transient-eddy moisture flux divergence in the tropics and, to a lesser extent, advection of moisture by the mean flow.

The mechanisms discussed here, in particular the mean-advection component of our scaling for the ITCZ width, appear to be distinct from the “upped-ante mechanism” of Chou and Neelin (2004). The upped-ante mechanism is based on changes in moisture advection, rather than changes in MSE advection, and suggests that convective zones should *narrow* with warming due to the advection of dry air from non-convective to convective regions. However, our results show that enhanced equatorward advection of low-MSE air in the descent region tends to *widen* the ITCZ. The precipitation changes discussed by Chou and Neelin (2004) occur largely over continents (see their Fig. 1), whereas aquaplanet simulations are analyzed here. This continental influence, the relationship between the advection of moisture versus MSE in tropical regions, and the resulting differences between the upped-ante mechanism and the mean-advection component of (8) should be investigated further.

It would be interesting to apply the ideas developed here to understand zonal variations in the climatological ITCZ width, and biases in the simulation of the ITCZ by comprehensive GCMs. The response of the ITCZ width to the seasonal cycle, to interannual variability, and to different radiative forcings could also be investigated using our energetic framework. Which of the physical processes, shown to influence the ITCZ width in idealized simulations over a wide range of climates, are important in the more moderate climate changes typically simulated by comprehensive GCMs? Compared to the idealized GCM used here, comprehensive models simulate additional processes in the climate system such as clouds and the interactions between water vapor and radiation. Such processes have been shown to affect the ITCZ width in fixed-SST aquaplanet models (Voigt and Shaw 2015) and are likely to also shape the ITCZ and its response in fully coupled GCMs. Finally, as discussed by Kang et al. (2009), the ITCZ width is sensitive to the parameterization of convection. Exploring this sensitivity to convection scheme systematically and running simulations with explicit deep convection are other ways to pursue this line of research further and improve our understanding of this key feature of the general circulation of the atmosphere.

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