Seasonal and CO₂-Induced Shifts of the ITCZ: Testing Energetic Controls in Idealized Simulations with Comprehensive Models

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ABSTRACT

The Tropical Rain Belts with an Annual Cycle and Continent Model Intercomparison Project (TRACMIP) ensemble—a multimodel ensemble of slab-ocean simulations in idealized configurations—provides a test of the relationship between the zonal mean ITCZ and the cross-equatorial atmospheric energy transports (AHT_{eq}). In a gross sense, the ITCZ position is linearly related to AHT_{eq} , as expected from the energetic framework. Yet, in many aspects, the TRACMIP model simulations do not conform to the framework. Throughout the annual cycle there are large excursions in the ITCZ position unrelated to changes in the AHT_{eq} and, conversely, substantial variations in the magnitude of the AHT_{eq} while the ITCZ is stationary at its northernmost position. Variations both in the net vertical energy input at the ITCZ location and in the vertical profile of ascent play a role in setting the model behavior apart from the conceptual framework. Nevertheless, a linear fit to the ITCZ– AHT_{eq} relationship captures a substantial fraction of the seasonal variations in these quantities as well as the intermodel or across-climate variations in their annual mean values. The slope of the ITCZ– AHT_{eq} linear fit for annual mean changes across simulations with different forcings and configurations varies in magnitude and even sign from model to model and we identify variations in the vertical profile of ascent as a key factor. A simple sea surface temperature–based index avoids the complication of changes in the vertical structure of the atmospheric circulation and provides a more reliable diagnostic for the ITCZ position.

1. Introduction

Where does rain fall in the tropics? The literature keeps circling between theories centered on momentum (Schneider and Lindzen 1977) or energy (Held and Hou 1980; Kang et al. 2008), between diagnostics based on the pattern of mass convergence (Chang 1973; Lindzen and Nigam 1987; Back and Bretherton 2009) or of boundary layer moist energy (Emanuel et al. 1994; Nie et al. 2010; Singh et al. 2017), and between convective parameterizations based on mass (Kuo 1974; Davies et al. 2013) or on energy (Betts and Miller 1986) closures. The answer may very well not be unique, and instead may depend on the time scales under consideration and the geography of each tropical location. With this study,

our contribution to the debate is to examine the extent to which an energy-based diagnostic is appropriate to capture forced changes in the position of the annual-mean, zonal-mean rainband [which we refer to, in a lasting reminder of the debate highlighted in this paragraph, as the intertropical convergence zone (ITCZ)]. The configuration analyzed in this study is highly idealized and our scope is tightly focused: we use models with no land, no zonal asymmetry, and no dynamic coupling between the atmosphere and the ocean; we consider only seasonal and longer time scales of variability; and we limit our investigation to a single diagnostic of rainfall, namely the latitudinal position of its centroid.

A comprehensive exposition of the energetic framework for the position of the ITCZ is found in Kang et al. (2008), Schneider et al. (2014), and Donohoe et al.

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(2014b) and, with focus on necessary caveats and extensions, in Biasutti et al. (2018). Briefly, the relevant measure of atmospheric energy is the sum of the terms associated with humidity, temperature, and height, which combine into a quasi-conserved quantity known as moist static energy ($MSE = Lq + c_p T + gZ$, where q is the specific humidity, T is temperature, Z is geopotential, L is the latent heat of vaporization, c_p is the specific heat capacity, and g is gravity). In the annual and zonal mean, the ITCZ is at the boundary between two meridional cells that import moisture-rich air into the ITCZ via their low-level flow and export high geopotential air out of the ITCZ at the tropopause level. Under the assumption that transport by stationary and transient eddies is of secondary importance,¹ the transport of the net radiative energy entering the tropical atmosphere must be dominated by the mean meridional circulation (MMC). For straight ascent, the latitude where the branches of the MMC diverge is thus also the locus of null meridional energy transport. Indeed, in observations and comprehensive models (Donohoe et al. 2013; Marshall et al. 2014) the annual-mean Hadley cells flux energy poleward and the energy flux equator (EFE; the latitude at which the net vertically integrated meridional energy transport is zero) is approximately coincident with the ITCZ (Bischoff and Schneider 2014; Adam et al. 2016).

When the EFE is close enough to the equator that a linear approximation is valid, its displacement off the equator can be expressed as a function of the net energy input into the atmosphere from top-of-atmosphere and surface radiative and turbulent fluxes at the equator and of the atmospheric energy transport across the equator (AHT_{eq} ; Bischoff and Schneider 2014). Assuming constant energy input at the equator, the displacement of the EFE (and, in conjunction, of the ITCZ) away from the equator should be roughly linearly proportional to the AHT_{eq} .² This linear relationship between annual mean ITCZ position and vertically integrated atmospheric energy transport across the equator was first quantified by Kang et al. (2008) in an idealized setting, and has been identified more broadly in observations and models (e.g., McGee et al. 2014; Donohoe et al. 2013)—although not universally, as we will discuss.

¹ The first assumption holds trivially in a zonally symmetric setup, and the second depends on the weakness of gradients across the tropical atmosphere, compared to the steady gradients between the deep tropics and the subtropics; we will return to this assumption in the discussion session.

² By the same approximation, changes in net equatorial energy input can cause shifts in the EFE in the absence of changes in cross-equatorial energy transport (Bischoff and Schneider 2014).

During its seasonal migration, the rainband shifts much less than the Hadley cells boundary and the EFE, MMC edge, and ITCZ do not overlap. Nevertheless, a linear relationship is still found between seasonal variations of the ITCZ and AHT_{eq} (Adam et al. 2016) and Donohoe et al. (2013) suggest that it is this linearity that underpins the linear relationship between *annual mean* AHT_{eq} and ITCZ across climatic states of different epochs or simulations by different models (Donohoe and Voigt 2017). The premise is that annual mean changes in the ITCZ position are the result of modulations of the persistence in different seasonal states, and thus the slope of the ITCZ– AHT_{eq} relationship ought to be quantitatively similar in the seasonal and intermodel or interclimate case. This is the case in CMIP5-class models, suggesting that the dynamics of seasonal migrations are relevant to past and future ITCZ shifts. (The question of whether most significant changes in tropical rainfall are fruitfully interpreted as zonal shift is a separate issue; Biasutti et al. 2018). In this study we test this formulation of the energy framework for the ITCZ position, and in particular we examine whether the ITCZ– AHT_{eq} relationship is accurately described as linear and whether the ITCZ– AHT_{eq} slope is approximately constant across the seasonal cycle and different climatic states, and across different models.

We use a multimodel ensemble of AGCM simulations coupled with a slab ocean of fixed depth in aquaplanet configuration (named TRACMIP, for Tropical Rain Bands with an Annual Cycle and Continent Model Intercomparison Project; Voigt et al. 2016). The absence of zonal asymmetries avoids stationary eddies that would complicate the relationship between the mean meridional circulation and the transport of energy (stationary eddies dominate the cross-equatorial AHT in reanalysis data; see Table 1 in Marshall et al. 2014), but transient eddies can exert their influence on the Hadley circulation (Schneider 2006). Energy is conserved at the boundary between the atmosphere and the ocean (contrary to the case of prescribed SST), but we avoid variations in ocean heat transports.³ All models except one (the CALTECH model) include the full effects of water vapor and clouds. The seasonal cycle is simulated and the response to quadrupling CO_2 includes a northward shift of the zonal mean ITCZ. Thus, the TRACMIP ensemble constitutes an ideal dataset with which to address the robustness of the relationship between the zonal mean ITCZ position and AHT_{eq} across the seasonal time scale and forced climate changes.

³ We discuss the appropriateness of disregarding coupling of ocean and atmospheric energy transport further in the conclusions.

The robustness of the relationship between ITCZ position and cross-equatorial energy transport has been investigated before in similarly idealized configurations (e.g., Merlis et al. 2013a; Seo et al. 2017; Wei and Bordoni 2018; Shaw et al. 2015) and in more realistic ones (e.g., Hill et al. 2015; Roberts et al. 2017; Green and Marshall 2017). In realistic configurations, the ITCZ–AHT_{eq} relationship is mostly disrupted by changes in oceanic circulations. More relevant to slab-ocean configurations such as ours are the effects of changes in the effective vertical energy stratification of the atmosphere [i.e., gross moist stability (GMS); Neelin and Held 1987; Held 2001; Raymond et al. 2009]. For example, Merlis et al. (2013a) find that stratification changes overcompensate for orbitally induced energy imbalances between hemispheres, causing the mass circulation response—and with it the ITCZ shift—to be opposed to the energy transport response. Seo et al. (2017) show that changes in GMS can determine CO₂-induced shifts in the ITCZ and that they are model dependent. Recently, Wei and Bordoni (2018) showed that the phase mismatch between the seasonal movements of the EFE and of the ITCZ can also be explained by changes in GMS related to changes in the vertical profile of ascent in the ITCZ. We expand on these studies by using a broader set of models and investigating both the annual cycle and the annual mean response to external forcings.

As a yardstick against which to measure the accuracy of the energy-based diagnostic, we employ a diagnostic based solely on sea surface temperature (SST), namely the interhemispheric difference in tropical SST. We choose this bulk measure because it has often been used in explaining ITCZ shifts, especially in the paleo context (e.g., McGee et al. 2014), and its relation to the energy framework is most direct: If the ITCZ–SST difference relationship were stronger than the ITCZ–AHT_{eq} relationship, this would suggest that boundary layer constraints on the ITCZ position are more stringent than those provided by the whole-atmosphere energy budget—at least in the context of TRACMIP.

In what follows we will first (section 2) provide more details about the multimodel ensemble of idealized simulations and the diagnostics used throughout the paper. The core of the paper (section 3) shows how the relationship between rainfall and energy fluxes is simulated in the TRACMIP ensemble over the seasonal cycle and across climates; it quantifies departures from the hypothesized near-universal linear relationship; and it identifies changes in the vertical profile of ascent in the ITCZ that are consistent with the variations in linear slope across models and climates. Throughout section 3, we also contrast the relationship between the position of the ITCZ and the cross-equatorial energy transport with

the relationship between the former and the interhemispheric SST difference. Section 4 provides a perspective for the interpretation of these results and discusses the limitations of our analysis due to model errors and simplifications. Section 5 provides a brief summary and points to future work.

2. Data and methods

TRACMIP was introduced in Voigt et al. (2016) and we refer the reader to that paper for a full description of the TRACMIP protocol and references for the participating models. Here, it will suffice to provide a very partial overview. TRACMIP comprises simulations by 14 atmospheric models (named and color-coded in Fig. 1) thermodynamically coupled to a slab ocean of uniform and constant depth (30 m). The control configuration is zonally symmetric (an aquaplanet), but the ensemble also includes simulations where a highly idealized continent of limited zonal and meridional extent straddles the equator. The suite includes simulations in aquaplanet and continent configurations, with preindustrial and quadrupled concentrations of CO₂ (AquaCTL, LandCTL, Aqua4xCO₂, and Land4xCO₂) and a nonzero orbital eccentricity (LandOrbit). (All these simulations are used in Fig. 5, but the rest of the paper is built on the zonally symmetric AquaCTL and Aqua4xCO₂ simulations.)

There are no explicit ocean currents in the TRACMIP simulations, but the effect of ocean heat transport is partially included by means of an ad hoc heat flux in the surface temperature equation. This prescribed “ Q flux” of heat is an idealization of the observed zonal mean and annual mean effect of ocean currents in causing heat convergence and divergence into the oceanic mixed layer. It provides a meridional asymmetry in all simulations, making the Northern Hemisphere warmer than the Southern Hemisphere and positioning the annual mean ITCZ north of the equator. This is the only source of interhemispheric asymmetry in all but the LandOrbit configurations. The Q flux is kept constant between CTL and 4xCO₂ simulations.

We computed monthly climatologies from the last 20 years of each simulation. Visual inspection of the global mean time series and of a comprehensive set of Gregory plots (Gregory et al. 2004) indicates that all simulations have reached statistical equilibrium before the period of our calculations. Tendency terms in the monthly energy budget were calculated as centered differences of climatological monthly values.

We diagnose the vertically integrated meridional flux of energy at latitude Y_o by integrating the net atmospheric energy input (TOA minus surface) from the

FIG. 1. (a) Median across the AquaCTL simulations of the annual mean mass streamfunction (contours; dashed indicates counter-clockwise, solid indicates clockwise), the energy transport by the mean meridional circulation (shaded contours; positive values are shaded in red and indicate northward transport), the vertically integrated total energy transport (thick black line at the top of the panel), the position of the energy flux equator (red segments marking the latitudes where the magnitude of the transport is less than 0.3 PW), and the zonal mean precipitation (plotted in blue at the top of the panel; only values above 5 mm day⁻¹ are drawn). (b) Climatological annual mean position of the ITCZ and vertically integrated atmospheric energy flux at the equator for each model in two sets of aquaplanet ensemble simulations that are distinguished only by the greenhouse gas forcing applied in each: AquaCTL (dots; linear fit in blue) and Aqua4xCO₂ (triangles; linear fit in red). Individual models are color-coded as labeled.

North Pole southward. We do the same calculation starting from the South Pole, and average over both calculations. For some of the models, the reported TOA fluxes do not add to zero in the global and annual mean, indicating a spurious source or sink of energy (Table 1); this apparent energy imbalance is subtracted in our calculation as a uniform correction. The implications of this bias for evaluating the energetic framework are discussed in section 4.

The decomposition of the vertically integrated energy transport into eddy and zonal-mean components calculated for the IPSL model are derived within an ad hoc extension of the AquaCTL simulation as online calculations, using instantaneous fields and integrating over the native model grid (F. Codron 2016, personal communication).

To calculate the position of the precipitation centroid we follow the algorithm proposed in Adam et al. (2016), but results are virtually indistinguishable if we use the algorithm of Frierson and Hwang (2012). We will refer to this quantity loosely as the precipitation centroid or the ITCZ position. The EFE is calculated as the interpolated latitude where the energy flux (assumed to vary linearly across adjacent grid points) is exactly zero. We have used this quantity (in place of the AHT_{eq}) to test the robustness of our conclusions on the appropriateness of an energy-based diagnostic for the ITCZ. We find quantitative differences, but we come to the same qualitative conclusions. Thus those results are not shown. In plots that contain reference to the EFE we prefer to explicitly indicate the diffuse nature of this quantity (especially in view of the uncertainties in the meridional

profiles of energy transport) by denoting the entire latitudinal range where the transport is less than 0.3 PW.

The surface temperature tropical differences are calculated as the difference of the area-mean SST over 0°–25°N minus 25°S–0°. Theories of the ITCZ position suggest other possible indices: Quasi-equilibrium theories (Emanuel et al. 1994; Plumb 2007) would have the ITCZ track the maximum boundary layer moist energy, and hence maximum SST over water. Convergence-based theories (Lindzen and Nigam 1987) would have the ITCZ track the Laplacian of SST. In our simple geometry, these measures are equivalent (Wei and Bordoni 2018), and they correlate very highly: Correlations are above 0.9 for the diagnostics that are presented in this paper: seasonal cycle, intermodel scatter in the annual mean, and interclimate scatter of the annual mean. Our results, thus, are robust to the choice of SST-based index.

3. The ITCZ–AHT_{eq} relationship across the seasonal cycle and across climates

The conceptual view of the tropical circulation codified in the energetic framework is summarized in Fig. 1a, which shows the zonal mean tropical circulation, rainfall, and energy transport in the AquaCTL TRACMIP multimodel median. The annual mean circulation reproduces the relationship expected from theory, comprehensive models, and observations. The Hadley cells are well defined in both hemispheres (solid and dashed lines indicates the mass streamfunction), although the southern cell is stronger and wider, extending across the

TABLE 1. The annual mean and global mean apparent energy imbalance at the TOA in the Aqua simulations (W m^{-2}). Note that the imbalance is spurious: the simulations are in statistical equilibrium over the period for which we calculate the energy flux.

	AM2	CAM3	CAM4	CAM5Nor	CNRM	ECHAM61	ECHAM63	GISS	IPSL	MeCTL	MeENT	MIROC5	MPAS	CALTECH
AquaCTL	−0.38	−0.03	0.02	−0.08	3.77	0.27	0.64	−0.02	1.10	0.02	0.00	0.76	0.88	−0.03
Aqua4xCO2	−0.23	0.47	0.04	0.07	4.75	−0.41	1.01	0.02	1.46	0.01	0.09	0.84	1.11	−0.03

equator; the region of ascent between the stream-function maxima is characterized by heavier rainfall (zonal mean precipitation above 5 mm day^{-1} is plotted in blue at the top of the panel); and the maximum precipitation coincides with the boundary between the cells. Each Hadley cell transports energy toward the tropics in the surface branch and away from the tropics in the upper branch (shaded contours), the AHT_{eq} is southward, and the boundary between the cells coincides with zero vertically integrated energy transport (the transport is indicated by thick black line at the top of the panel, latitudes where the magnitude of the transport is less than 0.3 PW are marked by red segments to indicate the position of the EFE). As expected, the EFE coincides with both the edge of the Hadley cells and the center of the (double-peaked) rainband; it coincides with the ITCZ.

Figure 1b shows the annual mean ITCZ position as a function of the AHT_{eq} in the AquaCTL and Aqua4xCO2 simulations (Land simulations confirm the results of Aqua simulations and are not presented here). Variations *across models* in the position of the rainband are roughly linearly associated with corresponding variations in the AHT_{eq} ; even allowing for the presence of an outlier (AM2 has a very different basic state from the other models and behaves as an outlier in many measures; Voigt et al. 2016) the linear relationship is significant at the 95% level, although the variance explained is only about 25%. The slope of the best-fit line between the two variables (hereafter simply “the slope” or “ITCZ– AHT_{eq} slope”) is quite similar across the two climates, although the confidence bounds are much too large to make strong statements about the degree of similarity. The slopes also match what has been reported for ensembles of comprehensive, realistic models [indeed, the depth of the mixed layer was chosen in order to produce a realistic seasonal excursion of the ITCZ, and thus the similarity of the slopes in TRACMIP aquaplanets and CMIP models is consistent with the sensitivity of the slope to mixed-layer depth presented by Donohoe et al. (2014a)]. When we compare the model scatter in the AquaCTL experiments (dots) with that in the Aqua4xCO2 experiments (triangles), we see that while the across-model slope does not change in an appreciable way, the two sets of simulations seem to sit on parallel lines. Again, the confidence bounds are broad, so that one cannot say that the intercepts are statistically different (from each other or from zero). Regardless, at least some models clearly simulate a northward shift of the ITCZ position in warmer climates that is not accompanied by a corresponding increase in the southward AHT_{eq} . This separation between AquaCTL and Aqua4xCO2 experiments suggests that TRACMIP simulations do not follow the expectation

FIG. 2. (left) Scatterplot of the climatological position of the ITCZ against (a) the AHT_{eq} and (c) interhemispheric tropical SST difference in the AquaCTL simulations. Small open circles are for individual models and the larger circles labeled by a number (1–12, for January–December) indicate the multimodel median; each color indicates a month, as in the color bar. The linear fit for each model is plotted in color (models are color-coded as in the legend throughout the paper) and for the median values is plotted in a thick black line. (right) The (b) ITCZ– AHT_{eq} and (d) ITCZ–SST seasonal slope calculated for each model (color), and for the median (black) and mean (dark gray) climatological months and for the ensemble as a whole (light gray); the median and mean of the individual model slopes are also shown as horizontal lines (black and gray, respectively). Confidence intervals on the individual slopes are marked by vertical segments. The seasonal slopes are calculated from the climatologies of the AquaCTL and Aqua4xCO2 (results for each simulation are bunched together as indicated in the x axis).

of a constant ITCZ– AHT_{eq} relationship across climates. How do such variations arise? And are they consistent with the hypothesis of Donohoe and Voigt (2017) that the ITCZ– AHT_{eq} relationship across climates is derived from the ITCZ– AHT_{eq} relationship within the (climatological) seasonal cycle?

a. Seasonal cycle of the ITCZ, AHT_{eq} , and MMC

The seasonal changes in the ITCZ position as a function of the AHT_{eq} in the TRACMIP aquaplanet simulations are explored in Fig. 2 (top panels). The scatterplot provides a visual impression of the strength of the linear relationship in the median and of the scatter across models. The bar plots provide a more quantitative assessment of the linear fits and compare the ITCZ– AHT_{eq} slope in simulations with preindustrial and quadrupled CO_2 . Let us at first focus on the AquaCTL simulations. Across the ensemble the AHT_{eq} becomes more negative as the ITCZ moves north, so that the seasonal ITCZ– AHT_{eq} slope is, in the median, negative. The linear fit passes through the origin, consistent with the expectation that an equatorially symmetric MMC would not transfer any energy across the equator. A negative slope and a small y-intercept describe the fit for most models (see colored lines and symbols in Fig. 2a), but for some models (AM2, IPSL, and CAM5Nor; Fig. 2b) the slope is not significantly different from zero

and the ITCZ variations are unrelated to AHT_{eq} variations, contrary to our expectations. Hence, the range in slope estimates across the models is larger than expected from the literature. The -4.4° latitude per PW of transport slope derived from the model median values of ITCZ and AHT_{eq} in each climatological month (thick black line in Fig. 2a and black symbol in Fig. 2b) is of the same order of magnitude as seen in previous work (Donohoe et al. 2013) but the slope derived from the ensemble as a whole (light gray symbol in Fig. 2b) is on the low side of most models: -1.9° latitude per PW. Under increased CO_2 , the ITCZ– AHT_{eq} seasonal slope undergoes a substantial change in a few of the models, resulting in the Aqua4xCO2 simulations showing a larger range of slopes and a less negative mean slope. Analysis of the Land experiments (not shown) confirms these qualitative results. This behavior suggests that the seasonal ITCZ– AHT_{eq} slope might undergo systematic changes as the climate warms, at least in a subset of the TRACMIP models, as will be investigated more in depth later (see Fig. 7).

Moreover, the linear fit is not as good as expected. The expectation from observations and comprehensive models with realistic boundary conditions is that the ITCZ and the AHT_{eq} would be arranged in an ellipse (Biasutti et al. 2018), consistent with a delay between the seasonal migration of the two quantities [Adam et al. 2016; the origin of the delay is investigated in Wei and

Bordoni (2018)]. In the TRACMIP simulations, though, the ellipse is highly distorted (Fig. 2a): from December through June the energy transport stays close to zero, even as the precipitation moves in latitude a great deal over its seasonal range (in the median May and December a weak positive energy transport can correspond to the ITCZ being either north or south of the equator) and vice versa values for September through December indicate that large changes in AHT_{eq} can correspond to negligible changes in the position of the ITCZ. The linear fit becomes even less appropriate in the Aqua4xCO₂ simulations (see the increase in the slope uncertainty for the median model going from AquaCTL to Aqua4xCO₂ in Fig. 2b), in which the energy transport between February and May changes substantially without a corresponding change in the position of the ITCZ (this will further be discussed below, in the context of Fig. 7). A similar behavior is also found in the aquaplanet simulations of Wei and Bordoni (2018).

For comparison with the energetic analysis, the bottom panels of Fig. 2 show the simulated seasonal relationship between the ITCZ position and the tropical SST difference. In this case, the linear relationship is much tighter for all models and for the model median (the correlation coefficient is 0.85, compared to 0.53 for the AHT_{eq}). The slope is positive (about 1.5°latitude per °C) for all models and there is no systematic change in slope depending on the amount of CO₂ in the atmosphere. How do we interpret the strength of this relationship? A few decades ago, Lindzen and Nigam (1987) would have seen in it the role of SST gradients, which establish the pattern of pressure gradients and low-level convergence in the atmospheric boundary layer and, hence, of rainfall. Convective quasi-equilibrium (Emanuel et al. 1994) would suggest that the gradient in SST ought instead to be viewed as indicator of the position of the maximum boundary layer moist static energy, and that it is the latter that is collocated with the ITCZ. Either way, one is tempted to interpret Fig. 2 as implying that boundary layer processes are sufficient to determine the position of the ITCZ, in contrast to most recent theories for the dynamics of the ITCZ (Schneider et al. 2014; Biasutti et al. 2018) and for the distribution of rainfall (Peters and Neelin 2006). We will return to this point in the discussion.

Let us reconsider the weakness of the seasonal ITCZ– AHT_{eq} relationship that we highlighted above—that is, changes in the position of the former being disconnected from changes in the latter when comparing December to June and the opposite when comparing September to December—in the context of the seasonal changes in the MMC. Figure 3 is patterned as Fig. 1a to show the seasonal evolution of the MMC in relation to the ITCZ and the atmospheric energy

FIG. 3. As in Fig. 1a, but for representative months: (from top to bottom) March, June, September, and December). Note that calculations of the monthly vertically integrated atmospheric energy transport are derived combining surface and TOA fluxes to tendency terms centered on that month.

FIG. 4. (left) Scatterplot of the Aqua4xCO₂–AquaCTL anomalies in the position of the ITCZ against the anomalies in AHT_{eq} and (right) interhemispheric tropical SST difference. Circles are the simulated anomalies; crosses are values obtained by multiplying the AHT_{eq} (SST difference, at right) anomalies by the value of the ITCZ– AHT_{eq} (ITCZ–SST) slope obtained from the seasonal cycle.

transport, but contrasts four representative months. In the TRACMIP aquaplanets, the solstitial months (December and June) are closer to equatorially symmetric states (see, e.g., the low values of SST differences in Fig. 2b), while the equinoctial months (September and March) are the months when the interhemispheric asymmetry is more pronounced (Fig. 2b). September shows the pattern that we expect from the energetic framework: a strong “winter” Hadley cell crossing the equator into the “summer” hemisphere, a well-defined peak in precipitation (close to its northernmost location), negative energy transport across the equator, and a sharply defined EFE north of the equator and collocated with the ITCZ. Six months later, in March, the circulation is somewhat reversed, with a stronger NH Hadley cell, but the asymmetry is muted and the winter cell barely reaches in the SH (remember that the implied ocean heat transport preferentially warms the Northern Hemisphere). Hence, while the winter cell transports energy away from the equator into the northern subtropics, there is no noticeable energy transport across the equator. Energy transport in the SH tropics is nonnegligible only south of 15°S, where the Hadley cell is present but very weak, and we presume that much of the transport might be the effect of eddies. In June and December the cross-equatorial cells are relatively weak and the circulation does not transport much energy across the equator (AHT_{eq} is close to zero and the EFE is very diffused). The energy transport is much larger at the poleward edge of the cross-equatorial cell and at the latitude of the opposite cell (in the SH in June and in the NH in December); this is where the MMC is driven by eddies (Schneider 2006) and thus we speculate that subtropical eddies might also substantially contribute to the energy transport. This behavior is

consistent with what seen in a full-radiation version of the CALTECH model by Merlis et al. (2013a,b), who point out that the energy budget constrains the Hadley cell and the ITCZ only when the latter is in its angular momentum-conserving regime. Overall, we still see a good correspondence between the cell boundary and the location of the ITCZ throughout the year, indicating that the lower-boundary moisture transport by the MMC is the dominant term in setting total moisture convergence and rainfall. But the strength of the MMC appears to be only weakly related to the strength of the AHT_{eq} and the latter is weakly related to the position of the ITCZ for most of the year.

b. Forced changes in the annual mean ITCZ and AHT_{eq}

The work of Donohoe and colleagues has suggested that the ITCZ– AHT_{eq} slope determined from the seasonal cycle ought to be predictive of changes in the annual mean quantities across climates: if we knew the change in the annual mean AHT_{eq} from one climate state to another, we should be able to diagnose the shift in the ITCZ, and vice versa. This is not to say that the changes in atmospheric energy fluxes from one climate state to another can be inferred from the forcing; this would imply that we could estimate a priori the response of clouds and oceanic circulation [a tall order, as shown repeatedly by Voigt et al. (2014), Shaw et al. (2015), Voigt and Shaw (2015), Kay et al. (2016), and Roberts et al. (2017)]. Leaving aside, therefore, whether the exercise has any predictive power, we can test the assumption that under external forcing the climate system equilibrates to a new basic state without changing the relationship between the atmospheric circulation and the atmospheric movement of energy.

We test this idea in Fig. 4. Recall that in Fig. 1 we had showed that, as an ensemble, the Aqua4xCO₂ climates

FIG. 5. Scatterplot of the position of the ITCZ against the values of (left) AHT_{eq} and (right) tropical SST difference in all TRACMIP simulations, with different markers indicating a different simulation (see legend in the left panel) and color-coded by model as in Fig. 1. A linear fit for each model is also plotted in color.

had ITCZs shifted toward the north without a corresponding change in AHT_{eq} . Here we revisit the same data, but we compare, for each model, the annual mean ITCZ shift (between Aqua4xCO₂ and AquaCTL) actually simulated by the models with the one that is calculated a posteriori by multiplying the simulated annual mean AHT_{eq} changes by the ITCZ– AHT_{eq} slope derived by the seasonal cycle. Thus, we allow that each model produces slightly different ITCZ– AHT_{eq} seasonal slopes. The shifts predicted from the seasonal slope are typically much smaller than the simulated shifts, indicating that the linear ITCZ– AHT_{eq} relation at seasonal time scale is a poor approximation of the relationship that holds for across-climate changes of the annual mean quantities. Moreover, the tight linear relationship ($r = -0.8$) across the predicted anomalies (crosses in Fig. 4) indicates that variations in the estimated seasonal slopes are overall too small to account for the broad variations in the annual mean ITCZ changes, and the weaker relation ($r = -0.5$) ITCZ– AHT_{eq} in the latter case has a different origin (once more, even though the correlation is significant, AHT_{eq} variance explains a small fraction of the ITCZ variance). Yet, Fig. 4 does indicate not just the presence of a relationship between CO₂-induced changes in rainfall and energy transport, but indeed an amplified sensitivity, relative to the seasonal case: the typical TRACMIP model produces a larger shift in the ITCZ position for a certain amount of AHT_{eq} than one would expect from the seasonal cycle. This is consistent with the unexpectedly strong northward shift of the ITCZ in the Aqua4xCO₂ simulations highlighted in Fig. 1b (recall the parallel fit lines). We now turn to the same analysis on the relationship between interhemispheric differences in tropical SSTs and the ITCZ position (Fig. 4,

right). In this case, the linear relationships are tighter ($r = 0.9$ for both the simulated and predicted anomalies, shown respectively by circles and crosses), but the same considerations on the magnitude of the anomalies apply: the seasonal cycle underestimates the sensitivity of the ITCZ position to CO₂-induced changes in the SST difference. For a few of the models, the difference is a factor of 2. Again, we interpret these relationships to imply that 1) boundary layer dynamics are a dominant determinant of ITCZ position and 2) external forcings act to change the annual mean state in ways more complex than a simple modulation of the basic-state seasonal cycle.

We expand our investigation of variations in the ITCZ– AHT_{eq} slope beyond just the effect of quadrupling CO₂ in the aquaplanet configuration by looking at variations across all the available TRACMIP simulations (including Land) for each model (Fig. 5; see also Table 2). Even though there are few points to constrain each slope (we perform the calculation if at least 4 of the 5 TRACMIP simulations are available), a clear picture emerges. For most models, all climates are well aligned along a linear ITCZ– AHT_{eq} relationship consistent with more negative AHT_{eq} for an ITCZ located farther north (correlations are close to -1), but even in the case of such models the slopes are model dependent and vary over a wide range (close to 1 to over 20° per PW), in clear contrast with the much smaller variations seen in the seasonal AquaCTL slopes. Moreover, there are exceptions: the CNRM and CAM3 models show a weak relationship between the equatorial energy flux and the position of the ITCZ (Table 2). Two more models show a linear relationship, but of opposite sign of the expected (see the slope of the fit lines in Fig. 5 and in Table 2). For CAM4 (aqua line), the slope of the relationship is large and positive, indicating that the position of the ITCZ

TABLE 2. The slope (and correlation) of the linear fit between the annual-mean ITCZ and either (top) AHT_{eq} or (bottom) SST difference across the climates simulated in different TRACMIP configuration for each of the models for which we had at least four simulations.

	AM2	CAM3	CAM4	CAM5Nor	CNRM	ECHAM61	ECHAM63	GISS	IPSL	MeCTL	MeTENT	MIROC5	MPAS	CALTECH
ITCZ- AHT_{eq}	-8.7 (-0.8)	-1.3 (-0.2)	25.6 (0.9)	-0.8 (-0.9)	25.5 (0.5)	-13.3 (-0.9)	-7.2 (-1)	n/a	20.8 (0.9)	-14.3 (-1)	-22.4 (-1)	-6.1 (-0.9)	-11.5 (-0.9)	-1.2 (-0.8)
ITCZ-SST	2.9 (0.9)	1.9 (0.8)	4.1 (1)	2.9 (1)	2.6 (1)	3.3 (1)	2.8 (1)	n/a	1.9 (1)	4.0 (1)	3.9 (1)	1.5 (1)	2.6 (1)	-0.3 (-0.5)

varies appreciably across climates while the AHT_{eq} varies only little (in the direction of mildly reduced southward transport for a poleward shift of the annual mean ITCZ). The IPSL (dark purple) shows a more complex behavior: the AquaCTL, LandCTL, and LandOrbit simulations (all experiencing preindustrial levels of CO_2) follow the expected negative covariance between AHT_{eq} and the ITCZ but, as CO_2 is quadrupled, the annual mean ITCZ shifts to the north by a few degrees, while the southward energy transport is somewhat reduced; the changes between CTL and 4x CO_2 climates are dominant and the overall linear fit has positive ITCZ- AHT_{eq} slope.

To explain what process might cause the ITCZ- AHT_{eq} relationship to change sign in a warmer climate, we compare changes in the IPSL models with two other models with different behavior: CNRM, for which climatic changes in the annual mean ITCZ position are uncorrelated with changes in the AHT_{eq} , and ECHAM6.1, for which the ITCZ- AHT_{eq} slope is negative under GHG forcing. Specifically, we compare changes in the profile of vertical motion in the ITCZ (calculated as a 20° band around the precipitation centroid for each month, and then averaged over the full year). Figure 6 shows a deepening of the ascent profile at the tropopause level and a weakening of the circulation, consistent with established theory (Hartmann and Larson 2002; Held and Soden 2006), for all full-physics models (CALTECH is an exception). The three models highlighted in color show different vertical velocity responses below 200 hPa: in ECHAM6.1 warming acts to reduce ascent mostly below 600 hPa; in CNRM the opposite is true and the reduction is maximum at 300 hPa (so that a doubly peaked profile in AquaCTL is changed to a nearly uniform profile in Aqua4x CO_2); and in IPSL the profile remains single peaked and its bottom heaviness is enhanced. A change toward a bottom-heavy profile of ascent is likely associated with negative anomalies in the gross moist stability (Raymond et al. 2009), that is, with reduced vertically integrated energy transport for the same amount of mass transport by the circulation. The increased bottom heaviness of the IPSL and CNRM model is consistent with their simulation of a reduction in the southward AHT_{eq} even in the face of a northward shift of the ITCZ in response to quadrupling CO_2 . A bulk measure of bottom-heaviness of the ascent profile (proportional to the difference between ascent above and below 500 hPa, but results are insensitive to the exact definition) qualitatively captures these profile changes and highlights the differences across models in their responses to increased CO_2 . Across TRACMIP models, the changes in bottom heaviness due to CO_2 quadrupling (Fig. 6c) correlate

FIG. 6. CO_2 -induced changes in the vertical profile of vertical velocity within the ITCZ. (a) The AquaCTL (thin lines) and Aqua4xCO2 (thick lines) vertical profiles of annual mean vertical motion (Pa s^{-1}) within the ITCZ band in each model [highlighted models are color coded as shown in (c), while the remaining models are in gray; to enhance visibility the range shown is less than the full range of the models' omega]; vertical levels are given in hPa. (b) As in (a), but for the Aqua4xCO2–AquaCTL annual mean omega anomalies. (c) Aqua4xCO2–AquaCTL annual mean anomalies in a bulk measure of bottom heaviness of the vertical motion profile within the ITCZ (broad bars), arranged in ascending order by the climate change ITCZ–AHT_{eq} slope (thin transparent bars; GISS model is missing).

with the ITCZ–AHT_{eq} slopes estimated from the Aqua and Land simulations (Fig. 5; see also Table 2) at 0.4. This correspondence is suggestive that 1) changes in bottom-heaviness affect the ITCZ–AHT_{eq} slope and that 2) changes due to CO_2 quadrupling are dominant over, or similar to, the changes due to the introduction of the continent (careful examination of Fig. 5 indicates that this is true for all models, with the exception of AM2). Nevertheless, the correspondence is weak; in particular, for ECHAM6.3 an increase in bottom heaviness coexists with a negative ITCZ–AHT_{eq} slope, and the opposite is true for CAM4. Even if our interpretation is correct (i.e., even if conditions 1 and 2 above both hold), it is possible that the coarseness of the two-layer difference is insufficient to capture the key aspects of changes in vertical ascent profiles. It is also possible that changes other than those of the Hadley circulation itself (e.g., in energy input or in eddy activity) are more significant.

Regardless of these caveats, we can state that under CO_2 forcing:

- 1) Changes in the multimodel mean ITCZ position exceed what one would expect from the corresponding changes in AHT_{eq} and the knowledge of the CTL ITCZ–AHT_{eq} slope [as derived from either the scatter across models in the CTL annual mean values (Fig. 1b) or the multimodel mean relationship across CTL seasonal values (Fig. 4a)].
- 2) Model differences in the climate-change ITCZ–AHT_{eq} slope are consistent with changes in the profile of annual mean ascent in the ITCZ, such that a tendency toward more bottom-heavy or more

top-heavy profiles is linked with a tendency toward more positive or more negative slopes (Fig. 6).

Let us now compare Figs. 5a and 5b. We leave aside the CALTECH model, which produces negligible anomalies in all quantities (ITCZ position, AHT_{eq}, and SST differences; see also Fig. 13 in Voigt et al. 2016) and for which the linear fit between the ITCZ position and the tropical SST difference is poor (see Table 2). The rest of the ensemble shows very consistently a positive ITCZ–SST linear relationship, but the linear slopes vary across models by close to a factor of 3 (1.5° to 4° latitude per $^\circ\text{C}$). Note that the ITCZ–SST slope estimated from the seasonal cycle (Fig. 2) corresponds to the smaller end of the spectrum for annual mean values across different climates. This is consistent with the underestimation of CO_2 -forced variations obtained using seasonal slopes noted while discussing Fig. 4.

c. The seasonal expression of the CO_2 -induced changes in ITCZ and AHT_{eq}

We have shown that, in a subset of models, under CO_2 forcing, 1) the northward shift of the ITCZ is highly seasonally dependent (Fig. 13 of Voigt et al. 2016), 2) the seasonal ITCZ–AHT_{eq} slope is noticeably reduced (Fig. 2b of this paper), and 3) the climate-change ITCZ–AHT_{eq} and ITCZ–SST slopes differ from their seasonal counterparts (Fig. 4, or compare Figs. 2 and 5), suggesting that changes in the annual mean position of the ITCZ cannot be obtained as linear combination of the seasonal extremes. Therefore, we now turn our attention to how the seasonal cycle in the ITCZ–AHT_{eq} space changes under increased CO_2 .

FIG. 7. Scatterplot of the Aqua4xCO₂–AquaCTL monthly anomalies in the position of the ITCZ against the anomalies in AHT_{eq}; the small open circles are for individual model (to enhance visibility of the median points, not all the data points are included within these axes limits), the large circles are the multimodel median values color-coded and numbered by calendar month. The black solid line is the linear fit across the median months; note that it does not go through the origin.

Figure 7 shows the CO₂-forced changes in the monthly climatology of the ITCZ position as a function of changes in AHT_{eq}. The shift of the precipitation centroid is more extreme in JFM (when the rainband in the SH is especially weakened), but it is positive year-round (Fig. 7; see also Fig. 13c in Voigt et al. 2016). In contrast, the changes in AHT_{eq} are evenly divided between positive and negative values, corresponding to the months with least and most ITCZ displacement, respectively. There still exists a reasonably strong linear relationship between the multimodel median ITCZ displacement and the AHT_{eq} anomalies, although the scatter for individual models is extremely large. Nevertheless, the fact that the linear fit does not go through the origin implies that anomalies in energy transport associated with shifts in the Hadley cell are compensated either by changes in energetic stratification or by changes in energy input and eddy transport. The degree of compensation is different in different months: in April the southward AHT_{eq} is especially strengthened, even as the ITCZ is only moderately shifted to the north; in March the opposite is true and the southward AHT_{eq} is strengthened only moderately, even as the ITCZ is shifted much farther to the north; and in November the southward AHT_{eq} is actually reduced (the anomalies are positive), even while the ITCZ has moved slightly north.

The changes in the vertical profiles of ascent suggest that changes in gross moist stability within the ITCZ are a possible contributor. Figure 8 shows the ensemble mean profiles of vertical ascent and moist static energy in the ITCZ in each calendar month in the AquaCTL and Aqua4xCO₂ simulations and the Aqua4xCO₂–AquaCTL anomalies. The profile of MSE shifts to higher values and its midtropospheric minimum is

more pronounced and placed about 100 hPa higher (shifted from around 650 hPa to about 550 hPa). Overall, the profile of MSE changes is similar (close to parallel) from one month to the next, although there are some differences between spring and fall months around 900 hPa, with more pronounced low-level (around 800 hPa) warming/moistening during fall. Changes in the vertical profile of ascent are large nearly throughout the year, with all anomalous profiles showing a reduction of ascent at all levels below 200 hPa. The anomalous profiles present noticeable differences across the seasonal cycle, and these differences are especially noticeable at low levels. During March–May positive omega anomalies are largest in a broad maximum that extends from 600 to 900 hPa, indicating especially reduced ascent at lower levels and a shift toward slightly more top-heavy omega profiles. In the fall months, reduced ascent is concentrated around 600 hPa and anomalies are much reduced below 750 hPa, leading to a more pronounced bottom-heavy profile (as upper-level ascent is reduced more than lower-level ascent). A note of caution is warranted, though, as these anomalies are subtle and not completely robust to the choice of averaging method. We elected to show mean profiles, which are smooth and easier to read, but if instead of calculating mean anomalies we calculate the median of the anomalies (or the anomalies between the median profiles) we obtain somewhat different results (not shown). What is robust is the fact that the shape of the ascent profile changes noticeably and changes differently in different months. Given the midtropospheric minimum in MSE, a more top-heavy profile of ascent implies a more efficient export of energy out of the column, while bottom-heavy profiles are associated with net input of energy in the column. Therefore, the monthly ITCZ and AHT_{eq} anomalies shown in Fig. 7 can be explained (at least in part) by invoking how top-heavy ascent anomalies would amplify the negative AHT_{eq} anomalies produced by a northward shift of the ITCZ (April case), while bottom-heavy ascent anomalies would reduce the negative AHT_{eq} anomalies or, coupled with more low-level MSE at low levels, even lead to a change in sign (November case). The relationship between ITCZ position and AHT_{eq} over the course of the year is thus further distorted in Aqua4xCO₂ compared to AquaCTL (consistent with the larger uncertainty in the seasonal linear fit for Aqua4xCO₂ shown in Fig. 2b). A varied response to CO₂ across the annual cycle is consistent with the results of Merlis et al. (2013a,b), who argues that radiative forcings have a larger effect on the ITCZ and the Hadley cell during the portion of the year when the latter is in its angular momentum-conserving regime.

FIG. 8. (a) AquaCTL (thin lines) and Aqua4xCO2 (thick lines) multimodel mean profile of omega (Pa s^{-1}) for each climatological month, color-coded as in the color bar. (b) As in (a), but for MSE (in temperature units). (c),(d) As in (a),(b), but for the Aqua4xCO2–AquaCTL anomalies. Dotted lines close to the surface indicate that some models report missing values at those levels.

4. Discussion

The analysis above suggests that the ITCZ position and the AHT_{eq} are not as tightly linked as in early work on the energetic framework for the ITCZ (e.g., Kang et al. 2008; Donohoe et al. 2014b; McGee et al. 2014), and that some of the complications found by other studies in both idealized and realistic settings (e.g., Merlis et al. 2013b,a; Hill et al. 2015; Seo et al. 2017; Wei and Bordoni 2018) are evident in the TRACMIP ensemble. Specifically, we found that 1) during large parts of the seasonal cycle, seasonal variations in the ITCZ position and the cross-equatorial energy transport of the atmosphere are not linearly related, 2) the ITCZ– AHT_{eq} slope estimates

from the seasonal cycle and from annual-mean climate change are different, and 3) the ITCZ– AHT_{eq} slope differs substantially across models for both the seasonal cycle and annual-mean climate change. In the following, we review assumptions underlying the strictest formulations of the energetic framework and the extent to which they hold, or do not hold, in TRACMIP.

a. The tropical circulation exports excess energy out of the near-equatorial region

A basic premise of the energetic framework is that the deep tropical latitudes experience a net input of energy that needs to be transported away to reach thermal balance. While this premise is true in the annual

FIG. 9. (a) Latitude–month Hovmöller diagram of the multimodel median energy exported out of the column by the circulation (shaded; calculated from the net energy input and the atmospheric storage terms), and the zero contour of the net moisture convergence (red lines; calculated as precipitation minus evaporation). (b) Components of the annual mean vertically integrated atmospheric energy flux in the IPSL model, as a function of latitude. Red line: flux by the mean meridional circulation (MMC). Green line: flux by atmospheric eddies. Magenta line: total flux calculated in-line from total wind. Black line: the sum of the MMC and eddy components. Cyan line: total flux calculated offline from the climatological energy fluxes at the surface and top of the atmosphere.

multimodel median, it is not true everywhere in the tropics in individual seasons. Here we show (Fig. 9) that, in the TRACMIP multimodel median, for most of the year the input of energy into the near-equatorial atmosphere is small (or even becomes negative), so that the requirement that energy be exported from there is mute. During most of the year, models simulate little net energy gain (and thus need for export by circulation) out of the equatorial edge of the rainband and even net energy loss (and thus need for import) in the deep tropics in the DJF and JJA transition seasons. Energy is exported from the entire ITCZ band only during SON, when the rainband is in the Northern Hemisphere and, as was already discussed in relation to Fig. 3, the cross-equatorial Hadley cell is strong.

b. The zonal mean circulation is dominated by a deep overturning that exports energy out of the ITCZ

While both bottom-heavy and top-heavy ascent circulation import moisture at low-levels, a deep circulation with greater divergence above the minimum in the MSE profile is needed for the upper-level export to dominate and produce net MSE export. Yet, we have shown that the profile of ascent is highly variable in the TRACMIP models; that the importance of shallow contribution to the MMC also varies through the seasonal cycle; and that changes in the vertical profile of ascent correlate, although not strongly, with the observed differences in the ITCZ–AHT_{eq} slope across models and climates. These results are consistent with what is seen in other idealized simulations with different versions of the CALTECH models (Merlis et al. 2013a; Wei and Bordoni 2018) and smaller multimodel ensembles (Seo et al. 2017; Hill et al. 2015).

Nevertheless, we note that there is a large scatter across models in this behavior, and this too has been noted in the literature [compare the results of Levine and Schneider (2011) with Merlis et al. (2013a)]. The literature has linked deep ascent with the location of the SST (equivalently, MSE) maximum and shallow circulations with the location of strong SST gradients (e.g., Lindzen and Nigam 1987; Emanuel et al. 1994; Plumb 2007; Sobel 2007; Back and Bretherton 2009). The SST-based diagnostic introduced here is linked, given the simple geometry of our setup, to both the maximum and the gradients in the SST pattern, so it is not surprising that it might be better suited to detect the location of the ITCZ. In their analysis of the annual cycle in the CALTECH model (with a similar configuration to the TRACMIP AquaCTL simulation but a different treatment of the slab ocean), Wei and Bordoni (2018) also find that changes in vertical structure of ascent are associated with a disconnect between the EFE and the ITCZ and that the rainband is more tightly linked to the near-surface temperature (especially its Laplacian) than to measures of energetic transport.

c. Transient and stationary eddies are negligible

In the energetic framework, the energy transport out of the ITCZ is dominated by the Hadley circulation, while energy transport by transient and stationary eddies is negligible. In TRACMIP, the absence of zonal asymmetries in the boundary conditions make the assumption of negligible stationary eddies trivially true. But there is no theoretical reason to assume that eddy activity must be small in the tropics. Convective organization and atmospheric waves and disturbances can

create transient nonnegligible moisture gradients (Shaw and Pauluis 2012) and synoptic midlatitude eddies can penetrate the deep tropics, and indeed are key to the dynamics of the Hadley cells and the monsoons (Schneider 2006; Bordoni and Schneider 2008; Merlis et al. 2013a). The possibility that energy transport by transient eddies is comparable to the transport by the MMC is confirmed by an explicit calculation—performed in-line from instantaneous wind and thermodynamic fields (F. Codron 2016, personal communication)—for the IPSL model: the annual-mean energy transport in the AquaCTL simulation by the eddies is as large as that of the Hadley circulation even near the equator (Fig. 9). The same conclusion is reached by Wei and Bordoni (2018) for the CALTECH model and by Harrop et al. (2019) for the MPAS model.

We see substantial departures in the TRACMIP Aquaplanet simulations from the underlying assumptions of the energetic framework, and they severely complicate the conceptual picture linking the ITCZ, the Hadley cell, and the hemispheric difference in net atmospheric energy input. Our conclusions do not depend on our choice to focus on the ITCZ–AHT_{eq} relationship and in fact they also arise from a similar analysis based on the ITCZ–EFE relationship (not shown). Moreover, these results confirm previous work carried out with less comprehensive sets of models (Merlis et al. 2013a,b; Seo et al. 2017; Wei and Bordoni 2018).

The direct calculation of the energy transport in the IPSL model (Fig. 9) points to another important technical complication. We infer the annual-mean energy transport across a given latitude from the integral of the net energy input from the pole up to that latitude circle (section 2); this implicit calculation assumes no annual-mean storage of energy and thus that the energy lost by one region must be gained by the adjacent region. When models exhibit substantial deviations from a global-mean zero TOA energy balance (recall Table 1), spurious energy sinks and sources invalidate our implicit calculation of the energy transport. The resulting uncertainties in the diagnosed energy transport are difficult to quantify, but the comparison between the implied and directly calculated transport in the IPSL model (Fig. 9) indicates that they can be substantial.

5. Conclusions

The aquaplanet simulations in the TRACMIP ensemble were designed to provide an optimal configuration in which to study the relationship between the mean meridional circulation, the atmospheric transport of energy out of the tropics, and the near-equatorial rainband—a relationship known in the literature as the

energetic framework for the ITCZ. Specifically, the zonal symmetry would ensure that no stationary eddies would complicate the zonal mean picture, the water surface would ensure the absence of sharp gradients in surface humidity, and the motionless slab ocean would allow a closed energy budget at the surface so that the atmospheric energy budget would be controlled by the top-of-atmosphere budget. Yet, this study has shown that the conceptual model that underpins the energetic framework for the ITCZ shifts unexpectedly fails (at least in its more quantitative formulation) in this most forgiving of idealized configuration.

We have focused on the relationship between the rainfall centroid (i.e., the ITCZ) and the vertically integrated atmospheric energy transport across the equator and we have diagnosed the quality and the robustness of a linear model to describe such relationship. We have examined the relationship emerging 1) in the monthly-mean ITCZ north and south movement through the seasonal cycle and 2) in forced changes in the annual mean values of ITCZ position and AHT_{eq} across different climates. We have investigated ensemble-mean behaviors as well as inconsistencies across models of the TRACMIP ensemble. Throughout this analysis we have found that the ITCZ–AHT_{eq} relationship is variable and often weak, so that energy-based diagnostics perform less well than SST-based diagnostics.

Note that this does not necessarily imply that prescribed SST simulations would be able to perfectly capture the simulated ITCZ behavior. Indeed, the idealized study of Kang and Held (2012) has demonstrated that rainfall anomalies are larger in coupled than uncoupled simulations, even when the SST is forced to be the same in both cases. That study went further to conclude that the magnitude of ITCZ shifts could not be directly inferred from the magnitude of changes in tropical SST (but could from the oceanic energy fluxes that forced the simulations). Yet, Kang and Held (2012) also noted that this conclusion would weaken in cases when the TOA radiative flux or the total gross moist stability responded to the external forcing. This is exactly the case in the TRACMIP ensemble: changes in the net energy input and in the vertical structure of ascent in the ITCZ are substantial and affect both the seasonal relationship and the annual mean response to climate change. These changes are so large and so model dependent that they compromise the usefulness of an energy-based diagnostic, given that these aspects of the atmospheric behavior cannot be independently predicted. The SST field is more directly linked to the location of the surface wind convergence (Lindzen and Nigam 1987; Chiang et al. 2001; Back and Bretherton 2009) and the maximum MSE (Emanuel et al. 1994;

Singh et al. 2017) and the relationship of SST to the ITCZ is robust across models and climates. We note, nonetheless, that the slope of the ITCZ–SST relationship changes between seasonal and CO₂-forced variations (Fig. 4b), suggesting that annual mean values are not a linear combination of the extreme seasonal positions and, therefore, that the transition seasons do matter (Wei and Bordoni 2018). In other terms, the width of the ellipse in Fig. 2b, which indicates the range of possible ITCZ positions for the same interhemispheric SST difference, also matters for climate change.

The idealizations in TRACMIP are, of course, substantial; thus it might be unwise to directly transfer our conclusions to more realistic models and to Earth. The first issue is the lack of zonal asymmetries: The subtropical stationary eddy circulation has been shown to be of primary importance in the seasonal progression of the monsoons and, consequently, of the zonal mean precipitation (Shaw et al. 2015). The rotational circulation associated with monsoon might sufficiently disrupt the mechanism presented here as to make them of secondary importance. Equatorial zonal difference in the aggregation of convection (akin to those caused by warm pools and continental masses alike) can also affect the structure of the MMC (Popp and Bony 2019). A closer look at the TRACMIP simulations that include an idealized continent might shed light on this phenomenon. The second issue is the lack of interactive dynamics in the upper ocean: The surface wind in the Hadley cells drive an oceanic Ekman transport that fluxes heat out of the equatorial region; thus, the meridional energy transport in the atmosphere is tightly linked to the meridional energy transport in the ocean (Held 2001; Schneider et al. 2014; Marshall et al. 2014; Levine and Schneider 2011; Green and Marshall 2017). Considering the energy budget of the atmosphere separate from the energy budget of the ocean, as we have done here by imposing a fixed Q flux, is therefore considering an unrealizable state. In Singh et al. (2017) the inclusion of Ekman dynamics does substantially change the GMS of the atmosphere, but it does not disrupt the connection between the MMC and the surface MSE pattern. An extension of the model hierarchy to include interactive ocean heat transport (Klinger and Marotzke 2000; Levine and Schneider 2011) needs to be investigated in a multimodel GCM ensemble. The third major idealization is the infinite availability of surface water: Over land, we expect sharp gradients in the surface moisture available for evaporation and different patterns of surface temperature and MSE. Dry ascent will tend to track the maximum of dry static energy while moist ascent will track MSE, thus decoupling the shallow and deep circulations (the surface mass convergence that is the

original indicator of the ITCZ, from the concentrated band of rainfall that we have loosely called the ITCZ in this study). This complexity cannot be captured in the TRACMIP simulations, and again points to the need for an extended hierarchy.

A full theory of the tropical circulation will need to address all these issues within the context of a more complete hierarchy of models and integrations. The TRACMIP experience suggests that, in order to allow a full assessment of the processes at play, future intercomparisons should provide robust estimates of the budget terms for moisture, energy, and momentum: this will require the online diagnostic of transport terms calculated on model levels and in advective form.

It is surprising that the ITCZ–AHT_{eq} relationship appeared to be more robust—extending from the annual cycle to climate change—in complex models (Donohoe and Voigt 2017) than in the (supposedly) made-to-order idealized configuration of the TRACMIP ensemble. We can only speculate on why this might be the case. In particular, it is intriguing to note that shallow circulations are associated, in observations, only with monsoons and marine ITCZs located in the deep tropics (Australia, West Africa, and the eastern Pacific; Nie et al. 2010). They are not associated with the Asian and South American monsoons that are responsible for most of the solstitial cross-equatorial transport (Dima and Wallace 2003). Thus, model configurations (including with realistic continents or a much shallower mixed layer) that support ascent away from the deep tropics might be less susceptible to shallow circulations or less sensitive to their effect. A fuller understanding of such dynamics necessitates a deeper investigation of what produces the substantial seasonal variations in the vertical profile of ascent in aquaplanets, and whether the presence of land in different geographical configurations might disrupt or overwhelm such processes.

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