Dynamical constraints on the ITCZ extent in planetary atmospheres

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ABSTRACT

We study a wide range of atmospheric circulations with an idealized moist general circulation model to evaluate the mechanisms controlling intertropical convergence zone (ITCZ) migrations. We employ a zonally symmetric aquaplanet slab ocean of fixed depth and force top-of-atmosphere insolation to vary seasonally as well as remain fixed at the pole in “eternal solstice” runs. We explore a range of surface heat capacities and rotation rates, keeping all other parameters Earth-like. For rotation rates $\Omega_E/8$ and slower, the seasonal ITCZ reaches the summer pole. Additionally, in contrast to previous thermodynamic arguments, we find that the ITCZ does not follow the maximum moist static energy, remaining at low latitudes in the “eternal solstice” case for Earth’s rotation rate. Furthermore, we find that significantly decreasing heat capacity does little to extend the ITCZ’s summer migration off the equator. These results suggest that the ITCZ may be more controlled by dynamical mechanisms than previously thought; however, we also find that baroclinic instability, often invoked as a limiter on the extent of the annual and summer Hadley cell, appears to play little to no role in limiting the ITCZ’s migration. We develop an understanding of the ITCZ’s position based on top-of-atmosphere energetics and boundary layer dynamics and argue that friction and pressure gradient forces determine the region of maximum convergence, offering a new perspective on the seasonal weather patterns of terrestrial planets.
1. Introduction

One of the most prominent features of Earth’s large-scale atmospheric circulation in low latitudes is the intertropical convergence zone, or the ITCZ (Waliser and Gautier 1993), defined in this study as the latitude of maximum zonal mean precipitation. Associated with the ascending branch of the Hadley cell, the ITCZ is the region of moist uplift, and thus of high precipitation and deep convection, that occurs where the low-level winds of the two cells converge. During summer, this convergence zone migrates off the equator into the summer hemisphere, up to 10N in oceanic regions and occasionally as far as 30N in the case of the Asian summer monsoon (Yihui and Chan 2005).

The mechanisms that control the ITCZ, though, remain unclear. Ideally, the convergence occurs over the warmest surface waters. Indeed, in the northeast Pacific ocean, the ITCZ remains north of the equator throughout the entire year, coinciding largely with high sea surface temperatures (SSTs), which remain north of the equator even during northern winter (Janowiak et al. 1995). However, previous observations show that the ITCZ does not always coincide with the SST maximum and corresponding local sea level pressure minimum (Ramage 1974; Sadler 1975). In light of such observations, and given the importance of moisture transport to tropical communities, much attention has been paid in the literature towards identifying and understanding controls on the ITCZ (Waliser and Somerville 1994; Sobel and Neelin 2006; Schneider et al. 2014). Much of this work can be roughly divided into two theories for understanding the ITCZ: one based on thermodynamics and the other on momentum dynamics.

a. Thermodynamic theory

Thermodynamic theories posit that deep convection is thermodynamically controlled. Convergence and precipitation are determined by local vertical temperature and moisture profiles gov-
erned by the moisture budget and surface and radiative fluxes (Sobel and Neelin 2006). When applied with the “weak temperature gradient” approximation, some such theories successfully re-

construct tropical convergence and tend to predict maximum convergence and rainfall over the warmest surface temperatures (Neelin and Held 1987; Sobel and Bretherton 2000). When applied to convergence zones associated with zonally averaged overturning circulations and coupled to quasi-equilibrium theories of moist convection and its interaction with larger-scale circulations, these thermodynamic constraints argue that the ITCZ lies just equatorward of the maximum low-

level moist static energy (MSE) (Emanuel et al. 1994; Lindzen and Hou 1988; Privé and Plumb 2007; Bordoni and Schneider 2008). For this reason, the distribution of MSE has been extensively used as a diagnostic of the ITCZ position.

However, the ITCZ has also been shown to respond strongly to extratropical thermal forcings, with shifts of the ITCZ into (away from) a relatively warmed (cooled) hemisphere, indicating that forcings remote from precipitation maxima can influence the tropical circulation and convergence zones (Chiang and Bitz 2005; Broccoli et al. 2006). Such work reveals the role of the vertically integrated atmospheric energy budget in ITCZ shifts and has led to the development of another diagnostic, the energy flux equator, which is the latitude at which the zonal mean MSE meridional flux vanishes (Kang et al. 2008). In recent studies focused on global energy transports, the energy flux equator has been shown to be well correlated with the ITCZ’s poleward excursion into the summer hemisphere, and the energetic framework in general has proved useful for understanding the ITCZ (Kang et al. 2008, 2009; Chiang and Friedman 2012; Frierson and Hwang 2012; Frierson et al. 2013; Bischoff and Schneider 2014). Lastly, through its control on thermodynamic quantities, heat capacity has also been shown to impact the ITCZ, with convergence generally traveling farther poleward over surfaces of lower heat capacity (Fein and Stephens 1987; Xie 2004; Donohoe et al. 2014; Bordoni and Schneider 2008).
b. Dynamic theory

Dynamic theories use the boundary layer momentum budget to determine winds and hence convergence, showing that convection is driven primarily by boundary layer (BL) momentum dynamics. Perhaps the most influential of these studies, Lindzen and Nigam (1987) showed that the pressure gradients associated with even the small surface temperature gradients of the tropics have a substantial impact on low-level flow and convergence. Their model, built on tropical SST gradients, adequately reproduces the observed tropical convergence, though the model’s assumptions have been debated. Back and Bretherton (2009) address such concerns by testing and expanding upon Lindzen and Nigam (1987), showing that SST gradients in reanalysis data are indeed consistent with BL convergence, which in turn causes deep convection. Along a similar vein, Tomas and Webster (1997) found that in regions where the surface cross-equatorial sea level pressure gradient was weak, convection tended to coincide with the maximum SST, but in regions with a substantial cross-equatorial pressure gradient convection tended to lie equatorward of the maximum SST, also suggesting the importance of temperature gradients, as opposed to maxima, in driving the flow. Subsequent studies develop a theory to determine the location of the ITCZ based on the cross-equatorial pressure gradient, which drives anticyclonic vorticity advection across the equator to render the system inertially unstable (Tomas and Webster 1997; Tomas et al. 1999; Tomas and Webster 2010). Thus, convergence and divergence are shown to be separated at the latitude where the zonal mean absolute vorticity is equal to zero.

c. ITCZ on terrestrial planets

Examining the behavior of the ITCZ on other terrestrial planets could provide further insight into the mechanisms that control its movement. It has been argued, using general circulation models (GCMs), that analogous regions of seasonal convergence and ascent associated with the Hadley
cell exist on other planetary bodies, namely Mars (Haberle et al. 1993; Lewis 2003) and Titan
(Mitchell et al. 2006). The ascent region migrates significantly off the equator into the summer
hemisphere during summer solstice, perhaps even reaching the summer pole on Titan. Indeed,
there have been multiple observations of methane cloud activity near Titan’s south pole during
southern summer solstice (Bouchez and Brown 2005).

Factors that control the movement of the ITCZ—particularly what prevents it from extending
too far beyond the equator on Earth yet allows it to reach the summer pole on Titan—still remain
unclear. The far-reaching solstitial Hadley cells on Mars and Titan are often ascribed to the planets’
low surface heat capacities due to their lack of global oceans. But the extent to which the smaller
rotation rate of Titan and the smaller radii of both planets may also contribute to the seasonality
of their convergence zones is unknown. From classical dry axisymmetric theory, the width of the
Hadley cell expands with decreasing rotation rate and/or decreasing radius (Held and Hou 1980;
Caballero et al. 2008). Many parameter space studies using GCMs (Williams 1988; Navarra and
Boccaletti 2002; Walker and Schneider 2006; Mitchell and Vallis 2010; Mitchell et al. 2014; Pinto
and Mitchell 2014; Kaspi and Showman 2015) show that slowly rotating planets exhibit expanded
Hadley cells and effectively become “all-tropics” planets similar in circulation structure to Titan
(Mitchell et al. 2006). But no parameter space studies have been done using a moist GCM with a
seasonal cycle, and focusing on the ITCZ, as we do in this study.

In addition, the classical axisymmetric theory does not account for the effect of baroclinic eddies
(Schneider 2006). GCM studies have highlighted the influence of eddy momentum fluxes on the
Hadley circulation by studying the response of Earth’s Hadley circulation to seasonal transitions
(Walker and Schneider 2005; Bordoni and Schneider 2008; Schneider and Bordoni 2008; Merlis
et al. 2013) and the extent of the annual-mean Hadley circulation over a range of planetary pa-
rameters (Walker and Schneider 2006; Levine and Schneider 2011). It has been suggested that
the annual-mean Hadley circulation width may be affected by extratropical baroclinic eddies that limit its poleward extent (Schneider 2006; Levine and Schneider 2015). Though no work has extended this argument to consideration of how baroclinic eddies might influence the circulation, the above studies show that eddy momentum fluxes impact the tropical overturning in equinoctial and solstitial circulations; thus, the possibility that baroclinic eddies, by strongly impacting the width and strength of the summer cell, may influence the ITCZ deserves investigation.

We examine these many potential controls on the ITCZ’s movement using a moist Earth GCM of varying heat capacities, seasonal forcings, and rotation rates. The primary controls in question are that of heat capacity, low-level MSE, baroclinic instability, atmospheric energy balance, and BL dynamics. In section 2, we describe the model and experimental setup. In section 3 and 4, we evaluate theories relying on heat capacity, maximum MSE, and baroclinic instability. In section 5, we analyze the general circulation of our rotation rate experiments. Then in section 6, we present analysis of the BL dynamics and radiative energy balance for all experiments.

2. Methods

We use the moist idealized three-dimensional GCM described in Frierson et al. (2006) and Frierson (2007) based on the Geophysical Fluid Dynamics Laboratory (GFDL) spectral dynamical core, but with two major changes: 1) the addition of a seasonal cycle, and 2) long-wave optical depths that do not depend on latitude.

Radiative heating and cooling are represented by gray radiative transfer, in which radiative fluxes are only a function of temperature, thus eliminating water vapor feedback. There is no diurnal cycle. The convection parameterization is a simplified Betts-Miller scheme, described fully in Frierson (2007). The scheme relaxes the temperature and moisture profiles of convectively unstable columns to a moist adiabat with a specified relative humidity (70% in these simulations).
over a fixed relaxation time (2 hours). Standard drag laws are used to calculate surface fluxes, with drag coefficients determined by a simplified Monin-Obukhov scheme. The BL scheme is a standard K-profile scheme with diffusivities consistent with the simplified Monin-Obukhov theory. The lower boundary is a zonally symmetric slab mixed layer ocean with a constant depth of 10 m in the control case, corresponding to a heat capacity $C$ of $1 \times 10^7$ J m$^{-2}$ K$^{-1}$ and a thermal inertia timescale $\tau_f \sim 20$ days, where $\tau_f = \frac{C}{4\sigma T^2}$ and $T = 285$ K (Mitchell et al. 2014). Thus, sea surface temperatures are prognostic and adjust to ensure the surface energy budget is closed in the time-mean.

**a. Seasonal cycle**

We implement the seasonally varying top-of-atmosphere (TOA) insolation prescription from (Hartmann 1994, pp. 347-349), wherein the declination angle is approximated by a Fourier series that provides an empirical fit to Earth’s current insolation. The left panel of Fig. 1 shows the resulting seasonal cycle of insolation. The prescription does account for Earth’s eccentricity.

**b. Optical depth**

The latitude-dependent optical depth of the original model was suited for an equinoctial framework and is thus inappropriate for our seasonal framework where bands of precipitation and humidity fluctuate in latitude over the course of a year. In our model, the prescribed optical depth is independent of latitude, becoming a function only of pressure with a linear component, describing the effect of well-mixed greenhouse gases, and a quartic component, capturing the effect of water vapor confined to the lower troposphere. Parameters of the pressure-dependent optical depth are same as in Frierson et al. (2006), except the surface value of optical depth $\tau_0 = \frac{1}{2}(\tau_{0e} + \tau_{0p})$, where $\tau_{0e}$ and $\tau_{0p}$ represent the equator and pole, respectively.
c. Experimental setup

The model uses the primitive equations with T42 spectral resolution and 25 unevenly spaced vertical levels, with greater resolution in the BL. We conduct three primary sets of simulations: 1) we reduce the depth of the mixed layer (values shown in Table 1, Earth slab ocean depth as from Donohoe et al. (2014)) with all other parameters kept Earth-like (default parameters as in Frierson et al. (2006)) and the insolation cycle kept fixed; 2) we reduce the frequency of the seasonal cycle down to the extreme case where the planet is in “eternal solstice” (shown in the right panel of Fig. 1) with all other parameters kept Earth-like, done to observe ITCZ behavior over the longer timescales of fixed insolation; and 3) we adjust the rotation rate of an Earth-like planet from 4 times larger than Earth’s value down to 32 times smaller than Earth’s value, where parameters other than rotation rate (insolation, radius, gravity, etc.) are kept Earth-like and the insolation cycle is kept fixed. In addition to these eddy-permitting simulations, we run axisymmetric simulations for end-member rotation rates, with both seasonal and “eternal solstice” forcings.

All simulations are run for ten years. Values for the seasonal cases are composited over the last eight years (two years of spin-up). All solstitial time averages for each year of the seasonal cases are taken during a 20-day period centered around the time of maximum zonally-averaged northern hemisphere precipitation. Values for the “eternal solstice” simulations are averaged over the final year (nine years of spin-up).

3. Evaluating thermodynamic mechanisms

In this section, we address to what extent theories for the ITCZ position developed within the thermodynamic framework explain results in our simulated experiments. In particular, we focus on the impact of heat capacity and MSE on the ITCZ position.
a. Heat capacity

Ideally, the ITCZ moves farther over land than over ocean because of land’s lower heat capacity. The most notable manifestation of this is the Asian monsoon, Earth’s largest and most extensive monsoon that reaches up to 30N as it travels over the Indian subcontinent and mainland China (Yihui and Chan 2005). Furthermore, explanations for the Hadley cell’s larger migrations on Mars and Titan as compared to Earth often emphasize the lower surface heat capacities of those planets, since they lack global oceans. In an aquaplanet or slab ocean experiment, the heat capacity is synonymous with the ocean depth and previous slab ocean experiments have shown that the ITCZ remains very close to the equator throughout the seasonal cycle for ocean depths on the order of 100m (Donohoe et al. 2014; Bordoni and Schneider 2008). However, the ITCZ’s behavior for smaller ocean depths is less clear.

Fig. 2 shows the zonally averaged precipitation over the seasonal cycle for three cases of varying heat capacities (see Table 1 for heat capacity values, slab ocean depth values, and thermal inertia timescales), as well as over the final year of the “eternal solstice” simulation. There is little change in the position of the ITCZ as the heat capacity decreases to drastically small values. This suggests that while the heat capacity affects the migration of the ITCZ at larger values, there is a lower limit, namely the control value, under which the heat capacity no longer affects the ITCZ’s migration. In other words, it appears that when the slab ocean depth is at the control value we reach a limit where the associated timescale for the energetic adjustment to the lower boundary is so small compared to the timescale of the seasonal cycle of insolation that further reductions in energetic adjustment timescale do not make any difference.

We have focused on the surface heat capacity, but our “eternal solstice” simulation also addresses the effect of the atmospheric heat capacity on the ITCZ’s movement. Maximum insolation in
the “eternal solstice” case is fixed at the pole for ten years, much longer than the timescale for atmospheric adjustments, and still the precipitation band does not migrate towards the summer pole. Thus, it appears that reducing the timescale for atmospheric adjustments even further would not have any impact on the ITCZ migration, as was the case for surface temperature adjustments.

Together, the null results of reducing both surface and atmospheric heat capacities suggest that dynamical constraints, as related to rotation rate or radius for instance, may be operating in cases of low thermal inertia. The role of rotation in “forcing” the ITCZ towards the equator has been similarly put forth by Chao (2000) and Chao and Chen (2001), wherein two “forces” critical to monsoon onset are described as in balance: one, associated with Earth’s rotation, towards the equator, and the other towards the SST peak. The extent to which our findings relate to these “forces” is unclear, however, since we employ a markedly different experimental design and analyze the ITCZ behavior through the perspective of the boundary layer momentum budget rather than in the “forcing” framework of those studies.

The ITCZ’s limited response to reductions in heat capacity also suggests that on Titan and Mars other planetary parameters other than the surface heat capacities may be the primary controls on the excursions of their seasonal convergence zones. Indeed, the atmospheric heat capacity on Titan is actually quite large (cf. Mitchell et al. 2014), indicating that the dynamical effect of its smaller rotation rate and radius must dominate strongly over the large atmospheric heat capacity to enable convergence over the summer pole.

b. Maximum MSE

Theory for the location of the convergence zone, based on the assumptions of a moist adiabatic vertical thermodynamic profile in statistical equilibrium, i.e. convective quasi-equilibrium (CQE), and an angular momentum-conserving meridional circulation with a vertical boundary, argues that
the maximum zonal mean precipitation occurs just equatorward of the latitude of maximum zonal mean subcloud MSE (Emanuel et al. 1994; Privé and Plumb 2007). The low-level zonal mean MSE $[m] = c_p[T] + [\Phi] + L_v[q]$, where the brackets indicate zonal mean, is strongly correlated with surface temperature over a saturated surface, as in our aquaplanet simulations. Examining the ITCZ in the “eternal solstice” experiment provides further insight into the CQE argument by effectively eliminating energetic adjustment timescales, as noted in the previous section.

Fig. 3 shows the zonal and time-mean precipitation, circulation features, and low-level MSE for the “eternal solstice” case. Maximum MSE in this case is located at the summer pole. The ITCZ, though, remains at low latitudes. The maximum zonal and time-mean precipitation occurs at approximately the same latitude for both the seasonal and “eternal solstice” case, around 20-25N.

c. Discussion of thermodynamic mechanisms

Neither heat capacity nor MSE exert a dominant control on the ITCZ’s poleward excursion, suggesting dynamics may be primarily driving the flow rather than thermodynamics in our simulations. From Fig. 3, MSE gradients, rather than the MSE itself, essentially maximize at the latitude of maximum precipitation for both the seasonal and “eternal solstice” cases. This would seem to be consistent with the arguments of Plumb and Hou (1992) and Emanuel (1995), who demonstrate that in a moist convective atmosphere, a cross-equatorial Hadley circulation needs to exist (in place of a radiative equilibrium response) when the curvature of the subcloud moist entropy (or nearly equivalently MSE) exceeds a critical value. This theory therefore more precisely defines the location of an overturning circulation by suggesting a link between the extent of the cross-equatorial Hadley cell, and with it the ITCZ, and the low-level MSE curvature. Please however note that the criticality condition can only be applied to radiative-convective equilibrium profiles of the low-level MSE: once an overturning develops when this critical condition is met,
the circulation itself will determine the MSE distribution. Hence, this criticality argument cannot
be easily translated into a quantitative diagnostic of the ITCZ position for our simulations. We
do confirm that in an eternal solstice axisymmetric simulation run under our control parameters,
the extratropical moist entropy distribution is indeed subcritical with regards to the critical con-
dition calculated via a radiative-convective perpetual solstice experiment (not shown). Thus, at
least for that case, though the zonal MSE maximizes at the pole, the extratropical atmosphere is in
radiative-convective equilibrium and there is no circulation at those latitudes, consistent with the
arguments just described.

As we discuss in section 6, the simulated cross-equatorial circulations for all rotation rates ap-
proach the angular momentum-conserving solution (Held and Hou 1980; Caballero et al. 2008),
in which the potential temperature in the free troposphere adjusts through thermal wind balance
to the angular momentum-conserving winds. Together with energy conservation constraints, these
angular momentum-conserving arguments can indeed be used to determine the latitude of the as-
cending branch of the winter Hadley cell, which, while not equivalent to, correlates well with the
ITCZ position. The strong correlation in Fig. 3 between the ITCZ and the maximum MSE gradient
in both seasonal and “eternal solstice” cases is indicative of the importance of surface tempera-
ture gradients in determining convergence, arguing for the role of BL momentum dynamics, in
agreement with Lindzen and Nigam (1987) and Back and Bretherton (2009).

4. Baroclinic instability

The “eternal solstice” case presented in the previous section also addresses the impact of baro-
clinic instability on the ITCZ. It has been suggested that baroclinic eddies may limit the extent of
the Hadley circulation (Schneider 2006; Levine and Schneider 2015). Observational studies have
linked the contraction and expansion of the Hadley cell during El Niño/La Niña events to anoma-
lous meridional temperature gradients and subtropical baroclinicity (Lu et al. 2008; Nguyen et al. 2013). Since the summer cell is very weak compared to the winter cell during solstice, it is possible that baroclinic eddies might limit the excursion of the cross-equatorial winter cell into the summer hemisphere. Additionally, eddy momentum fluxes have been shown to affect the large-scale meridional circulation in a variety of idealized climates (Walker and Schneider 2006; Levine and Schneider 2011), and to play a large role in monsoonal transitions in solstitial circulations (Bordoni and Schneider 2008; Schneider and Bordoni 2008; Merlis et al. 2013). During peak solstice, eddy momentum fluxes are relatively weak in the region of ascent and the cross-equatorial winter circulation is nearly angular momentum-conserving, shielded from eddies by upper-level easterlies; but on the poleward flank of the winter cell in the summer hemisphere, eddy momentum fluxes, though weaker than in the winter hemisphere, largely balance the westward Coriolis force from the equatorward flow in the upper branch. It remains unclear whether this extratropical baroclinicity is responsible for limiting the migration of the cross-equatorial winter Hadley cell, and therefore the ITCZ, into the summer hemisphere.

From Fig. 3, in the seasonal case poleward of the MSE maximum, there is a small gradient, suggesting baroclinic eddies may be present and preventing the winter Hadley cell from extending farther polewards. However, in the “eternal solstice” case, no such gradient exists, indicating a complete lack of baroclinic activity in this region, with zonal MSE maximizing at the pole. Yet, the circulation does not become global and its poleward extent remains at low latitudes. These results, therefore, suggest that extratropical baroclinic instability plays no role in limiting the ITCZ’s poleward migration during solstice in our simulations. Furthermore, in a simulation with the same seasonal cycle and Earth’s rotation rate run under axisymmetric conditions—in which the formation of baroclinic eddies is entirely suppressed—the ITCZ and Hadley cell extent still remain at low latitudes (not shown).
Given that neither baroclinic instability nor the thermodynamic constraints of heat capacity and MSE maxima seem to control the ITCZ in our simulations, in the next sections we explore possible dynamical controls related to the BL momentum budget.

5. Rotation rate experiments

To explore the ITCZ through a more dynamical perspective, we run Earth-like simulations for varying rotation rates. This is roughly equivalent to varying radius since both parameters similarly impact Hadley cell width (Held and Hou 1980). We find the ITCZ, defined here as the latitude of maximum zonally and solstitially averaged precipitation, reaches the summer pole for $\Omega/\Omega_E = \frac{1}{8}$.

a. Precipitation

Fig. 4 shows zonal mean precipitation for several rotation rate cases. The precipitation band of the ITCZ moves farther off the equator towards the summer pole with each decrease in rotation rate, consistent with previous studies.

It is worth noting that in the quickly rotating cases, including the control case, there are small “patches” of polar precipitation separated from the main ITCZ band at lower latitudes. This local precipitation is not strong enough for the ITCZ as we’ve defined it to be located at the pole, but it is consistent with the fact that local maxima in MSE exist at the pole during solstice in all cases, as shown in Fig. 5. Since low-level humidity is essentially uniform in an aquaplanet, local SST correlates extremely well with MSE. Thus, polar maxima in MSE during solstice reinforce the argument that for some planetary regimes, the ITCZ does not simply follow maximum zonal SST or MSE. Please note that though solstitial averages were taken prior to these polar maxima in the quickly rotating cases (see vertical orange lines in Fig. 5), the zonal circulation remains at lower latitudes throughout the summer, as indicated by the main ITCZ band.
We also run simulations at slower rotation rates, down to 32 times smaller than Earth’s, and find the ITCZ reaching the summer pole in those cases as well, but they are not shown because their circulations are similar in structure to that of the $\Omega/\Omega_E = \frac{1}{8}$ case. After $\Omega/\Omega_E = \frac{1}{8}$, it appears the planet enters a regime where the winter Hadley cell becomes global with the ITCZ at the pole, precluding any farther migration with larger decreases in rotation. Similarly, the $\Omega/\Omega_E = 2$ and $\Omega/\Omega_E = 4$ cases are not shown due to their circulation structures largely resembling that of the control case, though their ITCZs are indeed closer to the equator than the control (see Fig. 8).

b. Circulation

The ITCZ is closely associated with the ascending branch of the Hadley circulation. The right columns of Fig. 6 and Fig. 7 show the zonally averaged meridional circulation and angular momentum contours during solstice for all rotation cases. Consistent with the precipitation, the cross-equatorial Hadley cell expands farther poleward for each decrease in rotation rate. Additionally, the summer cell is negligible when compared to the cross-equatorial winter cell for all simulations during the averaged solstitial time period.

In aquaplanet simulations of Earth with negligible surface thermal inertia, as the seasonal cycle transitions from equinox to solstice—representing monsoon onset over land-dominated regions such as the Asian monsoon region—the winter Hadley cell strengthens and its ascending upper branch becomes more angular momentum-conserving (Lindzen and Hou 1988; Bordoni and Schneider 2008; Schneider and Bordoni 2008). At solstice, upper-level easterlies shield the circulation from energy-containing midlatitude eddies and the eddy momentum flux divergence is weak, thus allowing streamlines to follow angular momentum contours in the ascending branch of the cross-equatorial winter cell. Poleward of this ascending branch, where the summer cell is significantly diminished and meridional temperature gradients are larger, eddy momentum fluxes
balance the Coriolis force at upper levels. We observe similar solstitial dynamics as the rotation rate is decreased in our simulations: streamlines in the ascending region of all cases generally follow angular momentum contours; and in all cases a region of upper-level easterlies (not shown) is maintained by the winter circulation, which continues to expand latitudinally with decreasing rotation rate down to $\Omega/\Omega_E = \frac{1}{8}$, where the circulation finally becomes global.

Thus, a regime change occurs after $\Omega/\Omega_E = \frac{1}{8}$, wherein three conditions hold for planets with that rotation rate and slower: 1) summer precipitation reaches the pole, 2) the winter cross-equatorial cell extends from pole to pole and has a latitudinally wide region of updraft as opposed to the meridionally narrow ascent region seen in the more quickly rotating cases, and 3) eddy momentum flux divergence is weak at all latitudes. A similar regime change was noted in the non-seasonal experiments of Walker and Schneider (2006), wherein the upper branches of the circulations for slowly rotating planets were nearly angular momentum-conserving around the latitude of the Hadley streamfunction extremum. However, as noted in the previous section, baroclinic instability appears to play no role in limiting the migration of the ITCZ.

c. Diagnostics for the ITCZ

Here we evaluate relevant diagnostics for the ITCZ, namely the Hadley cell extent, the maximum low-level MSE, and the energy flux equator. As in the previous section, the zonally averaged low-level moist static energy $\overline{m}$ is taken at 850 hPa, with the overbar denoting solstitial average. The Hadley cell extent $\phi_H$ is defined as the latitude where the cross-equatorial streamfunction, taken at the pressure level of its maximum value, reaches 5% of that maximum value in the summer hemisphere (Walker and Schneider 2006). Finally, the energy flux equator defined in Kang et al. (2008) as where the energy flux $F = \langle [m v] \rangle$ reaches zero, with the angled brackets denoting vertical integration. However, since $F$ doesn’t vanish until the pole for $\Omega/\Omega_E = \frac{1}{2}$ and slower during
solstice, here we define the energy flux equator as the latitude where the flux $F$ reaches 5% of its maximum value, similar to the Hadley cell extent definition. Fig. 8 shows these diagnostics, each normalized to the maximum zonally and solstitially averaged precipitation (the ITCZ), for all rotation cases. It also shows the latitude where the function $G = 0.5$, with $G$ defined in Eq. 4 in section 6.3.

The MSE maximum, Hadley cell extent, and energy flux equator occur poleward of the latitude of the ITCZ for all but the most slowly rotating case. These three values are generally well correlated (particularly at faster rotation rates). Indeed, the Hadley cell extent and energy flux equator, physically related to one another (and, by definition, nearly equivalent), are approximately collocated for each rotation rate. It is also clear from Fig. 8 that the ITCZ is associated with the ascending branch of the cross-equatorial winter Hadley cell but generally lies equatorward of its edge. However, the distance of separation between the ITCZ and the winter Hadley cell extent appears to increase with decreasing rotation rate, until the circulation enters the slowly rotating regime. We also note the larger discrepancy between the latitude of maximum MSE and the ITCZ latitude in the $\Omega/\Omega_E = \frac{1}{4}$ and $\Omega/\Omega_E = \frac{1}{6}$ cases. This is indicative of the increasing migration of the convergence zone as rotation rate slows: The distinction between the main precipitation band of the ITCZ and the polar precipitation becomes less clear and the circulation appears on the verge of entering the slowly rotating regime of global circulation, as demonstrated by the $\Omega/\Omega_E = \frac{1}{8}$ case.

That the maximum precipitation is slightly equatorward of the maximum MSE during solstice has been noted in both models and observations (Privé and Plumb 2007; Bordoni and Schneider 2008). Discrepancies between the energy flux equator and the ITCZ—in both directions, i.e. with the energy flux equator both undershooting and overshooting the latitude of the ITCZ—have also been observed in various models (Kang et al. 2008; Bischoff and Schneider 2014), further
emphasizing the need for a more robust predictor of the ITCZ extent, particularly in strongly
off-equatorial regimes. In the next section, we work towards developing an understanding of the
position of the ITCZ based on BL dynamics and TOA energy balance.

6. Evaluating dynamical mechanisms behind the ITCZ position

In this section, we analyze potential dynamic controls on the ITCZ position. Before delving
into the details, it might be useful to first give an overall qualitative picture of the mechanisms
at work in our simulations. The flow that leads to the ITCZ is part of the lower branch of the
cross-equatorial winter Hadley cell. Using the case of northern summer solstice as an example,
this flow is the northward BL flow between the equator and the northern edge of the winter cell
in the summer hemisphere. The edge of the winter cell itself is where the flow vanishes, at a
latitude analogous to the energy flux equator or the maximum MSE, and can be determined by
TOA energy balance (Held and Hou 1980; Lindzen and Hou 1988; Satoh 1994; Caballero et al.
2008). Meridional forces in the BL, primarily the northward pressure gradient force and southward
Coriolis force, govern the zonal mean flow. However, while eddy momentum flux divergence
fluxes and vertical advection are very small in the BL, nonlinear advective forces are not and so
the flow is not completely in geostrophic balance. The pressure gradient, Coriolis, and nonlinear
forces combine into a northward force that balances the southward drag. Since the flow must
vanish farther poleward at the Hadley cell edge—and indeed all the forces must vanish there,
except for in the slowly rotating regime where they cannot vanish before reaching the pole—there
is a flow transition that must occur that leads to the ITCZ.

Our simulations demonstrate this mechanism and also provide a scaling for the latitude of the
ITCZ’s poleward excursion with rotation rate.
The mechanism behind the ITCZ, as it appears from our analysis, is intimately tied to previous work done by Held and Hou (1980) and in particular by Caballero et al. (2008), who applied the energy balance arguments of Held and Hou (1980) to the solstitial circulation in order to determine the extent of the cross-equatorial winter Hadley cell into the summer hemisphere. The connection to the ITCZ lies in the idea that the Hadley cell edge as determined by these energy balance arguments corresponds to the point where the energy flux and boundary layer forces vanish, just poleward of the ITCZ.

In Held and Hou (1980), the Hadley cell extent given equatorially symmetric insolation is determined through two primary requirements: that the energy budget of the Hadley cell is closed, and that the temperature structure at the cell’s poleward edge matches the radiative-convective equilibrium profile. These two requirements are equivalent to saying that the TOA radiative imbalance integrated over the width of the Hadley cell is equal to zero, and that the TOA radiative imbalance at the latitude of the cell’s poleward edge is itself zero. Note that in these theories the winds in the upper branch of the Hadley cell are assumed to be angular momentum-conserving. With these requirements, it is possible to determine the Hadley cell extent, which is dependent on the thermal Rossby number such that \( \phi_H \propto (Ro)^{1/2} \) for \( Ro = \frac{gH\Delta H}{\Omega^2 a^2} \), where \( H \) is the tropopause height and \( \Delta H \) is the pole-to-equator radiative-convective equilibrium temperature difference.

Caballero et al. (2008) applied similar arguments to seasonal insolation and found that the solstitial Hadley cell extent followed a different power law:

\[
\phi_H \propto (Ro)^{1/3}
\]

(1)

Fig. 9 shows the scalings of the ITCZ and the energy flux equator with rotation rate. Cases slower than \( \Omega/\Omega_E = \frac{1}{6} \) were not included in the scaling (\( \Omega/\Omega_E = \frac{1}{8} \) is in the plot, but not the
scaling calculation) because the ITCZ’s progression with rotation rate is limited by the pole beyond that point: once the Hadley cell is global, it remains so for slower rotation rates. The $\Omega/\Omega_E = 2$ and $\Omega/\Omega_E = 4$ cases, however, with ITCZs correspondingly close to the equator, were included in the scaling.

Since $Ro$ scales as $\Omega^{-2}$, the solstitial Hadley extent as determined by Caballero et al. (2008) scales as $\Omega^{-2/3}$, and Fig. 9 shows a similar scaling in our simulations—both for the energy flux equator and the latitude of the ITCZ itself—despite the fact that Caballero et al. (2008) used a dry axisymmetric model. This may be associated with the dynamic characteristics of solstice in an aquaplanet simulation: during solstice, the upper branch of the winter Hadley cell is approximately angular momentum-conserving at the latitude of ascent, with local Rossby numbers $Ro \geq 0.6$, signifying the relatively weak impact of eddy momentum flux divergence (Bordoni and Schneider 2008; Schneider and Bordoni 2008), thereby approximating axisymmetric conditions. As a caveat to the similarities just described, we should note that the power laws of Held and Hou (1980) and Caballero et al. (2008) employ the small-angle approximation, which is most likely inappropriate for our most slowly rotating cases.

Plotting the insolation against the outgoing longwave radiation (OLR) visually illustrates these energy balance arguments. Given the second requirement of the theory, the Hadley cell edge is where the radiative imbalance is zero, i.e. where the insolation and OLR intersect. But given the first requirement, the budget is closed and so the integrated imbalance over the width of the Hadley cell is zero, meaning the Hadley cell is determined by an equal-area construction of the imbalance.

Fig. 10 shows the insolation and OLR for the end-member rotation rates, with and without eddies, as well as with and without “eternal solstice” forcing. The figure illustrates that the radiative structure of the deep tropics looks very similar across all parameters and indeed gives the approximate width of the Hadley cell. Though large-scale eddies clearly impact the circulation
(particularly at higher latitudes) and prevent the insolation and OLR curves from intersecting at the Hadley cell edges in most cases, the winter Hadley cell edge in the summer hemisphere corresponds roughly to the local maxima of OLR.

Thus, the Hadley cell extent can be approximately determined by the shape of the OLR curve. In the axisymmetric “eternal solstice” case at Earth’s rotation rate, for example, the summer hemisphere edge of the winter cross-equatorial Hadley cell is at $\sim 30^\circ$N, coinciding with the local maximum in OLR there. The Hadley cell extents plotted in Fig. 10 are defined as the latitudes where the cross-equatorial streamfunction, taken at the pressure level of its maximum value, reaches 2% of that maximum value, rather than when it vanishes entirely. This could account for the discrepancies between the insolation and OLR in the winter hemisphere, where the region of descent is relatively broad in latitude as compared to the narrow region of ascent in the summer hemisphere; but winter hemisphere eddies may also be contributing to the discrepancies in the eddy-permitting cases. The axisymmetric “eternal solstice” case, the most steady and without eddies, gives the clearest picture of the energy balance arguments, with the equal-area construction almost exactly matching the winter Hadley cell width. However, the same structure is also apparent in the control seasonal case: even though the insolation and OLR don’t quite intersect, the OLR profile flattens near the edges of the winter Hadley cell.

For the $\Omega/\Omega_E = \frac{1}{8}$ cases, on the other hand, the equal-area argument suggests the cell is global. In other words, the edges of the winter cell—in loose terms, since the OLR never actually intersects the insolation at either edge of the cell in any case—are essentially at the poles. In some sense, the cell’s edge must be at the pole because it cannot be any farther poleward than that.
b. Boundary layer dynamics

Our analysis of the BL dynamics will be conducted primarily through the lens of the momentum equations as presented by Schneider and Bordoni (2008), hereafter SB08, who studied Earth’s solstitial dynamics in the convergence zone using a dry GCM with a seasonal cycle. Following SB08, the BL steady-state momentum equations with drag represented as Rayleigh drag with damping coefficient $\varepsilon$ are:

\[ -(f + \zeta)\overline{v} \approx -\varepsilon\overline{u} \quad (2) \]

\[ (f + \zeta)\overline{u} + \frac{\partial \overline{B}}{\partial y} \approx -\varepsilon\overline{v} \quad (3) \]

where $\overline{B} = \overline{\Phi} + (\overline{u}^2 + \overline{v}^2)/2$ is the mean barotropic Bernoulli function with geopotential $\Phi$ and the overbar again denotes the time-mean. Formulating the momentum equation this way means that the Bernoulli gradient accounts for the pressure gradient force as well as nonlinear contributions.

Aside from approximating turbulent drag as Rayleigh drag, the other assumptions made here are that contributions from eddy momentum flux divergence and vertical advection are negligible, and indeed in our simulations those terms are about an order of magnitude smaller than the retained Coriolis, Bernoulli gradient, drag, and $\overline{\zeta u}$ terms (We include the Rayleigh drag approximation here because it will be used in the next subsection, but the drag force plotted in Fig. 6 and Fig. 7 is diagnosed directly from the model, calculated by horizontal diffusion).

Fig. 6 and Fig. 7 give a summary of these forces for each rotation case during northern summer solstice and the “eternal solstice” case, with all values vertically integrated over the BL. We define the BL as ending at 850 hPa, though for the more slowly rotating cases, the lower branch of the circulation reaches the free troposphere. For all cases, the ITCZ is well correlated with the latitude of maximum BL drag. Indeed, in the “eternal solstice” case, where the maximum MSE condition
failed, the ITCZ and latitude of maximum drag are exactly collocated. From the right column of Fig. 6 and Fig. 7, it is evident that for each case the ITCZ is located in the BL region of maximum southward drag, a region just equatorward of the edge of the winter Hadley cell.

This mechanism seems to break down for the most slowly rotating case, with the latitude of maximum drag lying far equatorward of the ITCZ. This may be due to the widening of the convergence zone but could also be related to the change in the convergence zone force balance from primarily geostrophic in the quickly rotating cases to something closer to cyclostrophic in the slowly rotating regime, with the nonlinear $\zeta u$ force becoming a dominant contributor to balancing the Bernoulli gradient force. Also in the slowly rotating cases, regions of strong meridional drag exist at equatorial latitudes. Though they do not appear in the mass flux contours, there are indeed secondary maxima of precipitation and vertical velocity in these regions. The mechanism for these secondary equatorial convergences is left for future work, but it is perhaps similar to that described in Pauluis (2004), where the cross-equatorial jump is due to a weak SST gradient.

It is also apparent from the left column of Fig. 6 and Fig. 7 that the ITCZ is associated with the maximum northward Bernoulli gradient force, consistent with the previous observation of the simulated ITCZ being well correlated with the maximum MSE gradient, given that temperature gradients determine pressure gradients. In many cases, in fact, the ITCZ is collocated with the maximum northward geopotential gradient, which lies just equatorward of the maximum Bernoulli gradient. This is notable in that it marks the importance of temperature (and therefore pressure) gradients in driving the convergence zone flow (Lindzen and Nigam 1987; Tomas and Webster 1997; Pauluis 2004; Back and Bretherton 2009). However, due to the increasing relevance of nonlinear advective forces (namely the $\zeta u$ force) as the ITCZ moves farther from the equator in the more slowly rotating cases, the linear theories of Lindzen and Nigam (1987) and Back and
Bretherton (2009) cannot be applied here, as they predict an ITCZ too far poleward in all but our control simulation.

Indeed, the significance of the $\zeta u$ force implies that classic Ekman theory arguments describing flow—wherein the balance of forces is primarily between the pressure gradient force, the Coriolis force, and turbulent drag—are inappropriate when considering solstitial convergence zone dynamics. According to Ekman theory, uplift maximizes where geostrophic vorticity maximizes, but in every one of our simulations geostrophic vorticity maximizes well poleward of the ITCZ during solstice (not shown), underlining the unsuitability of Ekman theory in solstitial situations and the importance of nonlinearity in determining the BL maximum convergence—a relationship also noted by Tomas et al. (1999).

c. Connection to SB08

We have just shown that the maximum meridional drag and maximum Bernoulli gradient adequately describe the ITCZ in a diagnostic sense. Here we take steps towards attaining a more predictive theory for the ITCZ’s location. The convergence zone momentum budget analysis in SB08 begins with equations (1) and (2) and arrives at expressions for the zonal and meridional winds in terms of a nondimensional function $G$, defined as:

$$G = \frac{\varepsilon^2}{\varepsilon^2 + (f + [\zeta])^2}$$

(4)

This function helps describe the solstitial convergence zone. For $G \to 1$, as seen from expression (2), the BL balance is primarily between the Bernoulli gradient force and friction. As $G \to 0$, the balance is primarily between the Bernoulli gradient force and the Coriolis force.

The connection to the BL convergence zone is that, during solstice, the zonal and time-mean $G$ profile transitions meridionally from values $\sim 1$ near the equator, to values closer to 0 farther
poleward in the region of ascent at the edge of the cross-equatorial winter Hadley cell. Since
\[ \bar{v} \approx -\frac{G}{\varepsilon} \frac{\partial B}{\partial y}, \]
this transition occurs in the convergence zone, equatorward of the Hadley cell edge.

Such a relationship led SB08 to approximate the region of greatest convergence, or the ITCZ, as
the region where \( G \approx 0.5 \). We observe a similar transition in our simulations, though note that the
latitude where \( G \approx 0.5 \) does not correlate well with the ITCZ position in any case (see Fig. 8).

Fig. 6 and Fig. 7 show the \( G \) profiles for each rotation case, where
\[ \varepsilon = C_d \left( \bar{u}^2 + \bar{v}^2 \right)^{1/2} / H_0, \]
with \( C_d \) being the surface drag coefficient of momentum and \( H_0 \) being the height of the BL (Lindzen
and Nigam, 1987). Note that \( \varepsilon \) is not a constant but is dependent on the surface winds, since the
drag force reduces to the surface stress when vertically integrated in the BL.

In each case, the ITCZ occurs as \( G \) decreases to zero, in most cases at a value closer to \( G \approx 0.1 \) –
0.2. It remains unclear how to apply the theory underlying the \( G \) function to an exact prediction or
scaling of the ITCZ latitude. The ITCZ appears to correlate with the curvature of the \( G \) function,
but we have not developed a theoretical basis for such a relationship. The transition occurs over
a larger latitudinal range as rotation rate decreases, consistent with the widening winter Hadley
cell and more extensive regions of convergence and precipitation in those cases. It is also notable
that at the latitude where \( G \approx 1 \), the zonal and time-mean absolute vorticity \( \bar{\eta} \) is approximately
zero in every case (not shown). This is consistent with the work of Tomas and Webster (1997),
in which the \( \bar{\eta} = 0 \) latitude demarcates between divergence and convergence, with divergence
equatorward of that latitude and convergence associated with inertial instability—producing the
ITCZ—poleward of that latitude.

Finally, Fig. 6 and Fig. 7 show that the same approximate force balance holds for each case. One
noteworthy difference however is that in the “eternal solstice” case, the extratropical geostrophic
force balance is in the opposite direction than it is in the seasonal case. This can be attributed
to thermal wind balance and the fact that MSE maximizes at the pole in the “eternal solstice”
case, resulting in radiative equilibrium in the extratropics wherein there is no circulation, as noted previously. Thus, the temperature profile controls the winds, producing high-latitude easterlies and a northward Coriolis force. The unique radiative character of the “eternal solstice” case may also be responsible for the stronger circulation and wider Hadley cell width than observed in the seasonal case, though the ITCZ itself remains at the same latitude.

7. Summary and Conclusions

We conduct a suite of experiments to test various controls on the seasonal excursions of the ITCZ using an idealized, aquaplanet Earth GCM. These controls include heat capacity, low-level moist static energy, baroclinic instability, atmospheric energy balance, and boundary layer dynamics. We find that decreasing the slab ocean depth beyond 10m does little to extend the ITCZ. We also find, through “eternal solstice” experiments, that the ITCZ is not always closely coupled with the maximum MSE and is also not limited by baroclinic instability: in the “eternal solstice” case, the maximum MSE is located at the pole and there is little to no baroclinic instability in the summer hemisphere, yet the ITCZ remains at low latitudes—exactly where it sits in the control Earth simulation.

We slow down the rotation rate of an otherwise Earth-like planet to examine the ITCZ as it migrates farther off the equator. We find the ITCZ reaches the summer pole for rotation rates \( \Omega/\Omega_E = \frac{1}{8} \) and smaller. Classic ITCZ diagnostics, namely maximum MSE, Hadley cell extent, and energy flux equator, are generally collocated with each other, but robustly lie poleward of the latitude of the ITCZ, with the distance of separation increasing as the ITCZ moves farther from the equator. Based on the ITCZ’s behavior across a range of rotation rates, we describe a framework for understanding the location of the ITCZ based on energy balance and BL dynamics—the latter being very similar in principle to work previously done by Schneider and Bordoni (2008).
TOA energy balance, based on the axisymmetric theory of Held and Hou (1980), determines the latitude poleward of the ITCZ where the flow vanishes. The ITCZ diagnostics mentioned above correlate with this latitude rather than the ITCZ itself, which is the latitude of uplift and convergence equatorward of the Hadley cell edge and closely associated with maximum BL drag and Bernoulli gradient.

Common throughout our investigation has been the importance of temperature gradients and by association pressure gradients. In the “eternal solstice” case where the maximum MSE condition fails, the ITCZ is approximately collocated with the maximum MSE gradient; and in all cases, the ITCZ is closely correlated with the maximum Bernoulli gradient force. This is in accord with dynamical studies of the past, particularly Lindzen and Nigam (1987), Back and Bretherton (2009), and Tomas and Webster (1997).

Such relationships are important when thinking about analogous systems of seasonal convergence on other planets. Our results suggest that it is primarily the planetary parameters associated with the angular momentum budget, i.e. the rotation rate and/or radius, that are responsible for Titan’s and Mars’s far-reaching convergence zones, rather than their low surface heat capacities. Indeed, the atmospheric circulations of the $\Omega/\Omega_E = \frac{1}{8}$ case and slower, which have intense polar precipitation and a global Hadley cell, are not too dissimilar from that of Titan, which itself has a rotation rate approximately one sixteenth of Earth’s and a radius one third of Earth’s. While we are not yet able to predict the poleward migration of the ITCZ given only planetary parameters, the axisymmetric scaling of Caballero et al. (2008) seems to be quite accurate when applied to our simulations, even though they are moist and eddy-permitting. It is left for future work to further develop our diagnostic ITCZ understanding into a more prognostic theory that can be applied to any terrestrial planet with seasonally migrating convergence zones.
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