Moist Hadley circulation: possible role of wave-convection coupling in aqua-planet experiments

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ABSTRACT

Aqua-planet simulations are conducted to advance the understanding and numerical modeling of the Hadley circulation and the intertropical convergence zone (ITCZ) for given sea surface temperature (SST). If SST is globally uniform, an ITCZ and a Hadley circulation that are nearly equatorially symmetric emerge spontaneously. Their strength varies over a wide range from being faint to climatologically significant depending on a tunable parameter of the model’s cumulus parameterization. In some cases, especially when a non-standard radiation scheme is used, asymmetric Hadley circulations formed along with long-lived tropical cyclones.

The tunable parameter affects the transient variability of tropical precipitation. In the runs in which well-defined near symmetric ITCZs formed, tropical precipitation exhibited clear signatures of convectively coupled equatorial waves. The waves can explain the concentration of precipitation to the equatorial region to induce the Hadley circulation. Also, the meridional structures of simulated ITCZs are consistent with those of dominant convectively coupled equatorial wave modes. The roles of the waves remain when SST is not uniform to some extent. By using a conceptual two-box model, it is shown that the distribution of latent heating can be interactively adjusted while a circulation is formed, so a room is left for transient disturbances to affect tropical climate. Angular momentum budget does not provide an effective thermodynamic constraint, since the baroclinic instability adjusts the angular momentum in the poleward branch of the circulation. Transient variability may have a broader impact on tropical climate and its numerical modeling than has been thought.
1. Introduction

The Hadley circulation and the intertropical convergence zone (ITCZ) are important components of the general circulation of the Earth’s atmosphere. A historically important and influential theory of the Hadley circulation is proposed by Held and Hou (1980, hereafter HH). HH offered a theory of the axisymmetric circulation that is driven thermally by Newtonian relaxation toward a radiative equilibrium temperature, which has a $\cos^2 \phi$ dependence on latitude $\phi$. The HH model is able predict a number of features of the Hadley circulation such as the meridional extent and the strength (if the relaxation time scale is given). It can also be extended to equatorially asymmetric cases to show that a heating maximum centered off the equator effectively drives the circulation (Lindzen and Hou 1988).

Later studies have shown that eddies affect the Hadley circulation substantially (e.g., Schneider 1984; Satoh et al. 1995; Becker et al. 1997; Walker and Schneider 2006). Using an idealized aqua-planet global model, Satoh et al. (1995) demonstrated that the Hadley circulation is enhanced and widened by vertical angular momentum transport by baroclinic eddies. Walker and Schneider (2006) showed the scaling relations of the Hadley circulation depending on a number of external parameters such as the planet radius, the rotation rate, and thermal conditions.

The distribution of the sea surface temperature (SST), which is given in aqua-planet simulations or in atmospheric general circulation models (AGCMs), is in reality affected by the atmospheric circulation. Thus, an understanding of the Hadley circulation and the ITCZ should eventually be established in the context of a coupled atmosphere-ocean system (e.g., Xie and Philander 1994, Xie 2005). Understanding how the atmosphere responds to prescribed SST is a critical step toward the understanding, which is actually not straightforward as reviewed below.

The ITCZ tends to be situated along zonally oriented SST peaks off the equator. Lindzen and Nigam (1987) proposed a simple theory with which climatological convergence in the tropical boundary layer is associated with minus the second derivative of SST, which tends
to peak around the SST peaks. While a part of the convergence contributes to the shallow boundary layer circulation (Zhang et al. 2004), a large portion of the remaining contributes to deep upwelling associated with the ITCZ. The extent to which the Lindzen and Nigam theory is applicable has been argued substantially, but recently Back and Bretherton (2009) showed its validity using a skillful linear mixed layer model and observational (satellite and reanalysis) data.

In numerical atmospheric models, however, a variety exists among the simulated relationship between the tropical precipitation and SST. Early studies by Numaguti (1993) and Hess et al. (1993) showed that in aqua-planet general circulation models with SST peaking at the equator, both single and double ITCZs can form depending on the cumulus parameterization used (in their cases, the moist convective adjustment scheme for the single ITCZ and the Kuo scheme for the double ITCZ). Although most modern AGCMs do not use Kuo-type closures based on moisture convergence, many of them still suffer so-called the “double ITCZ syndrome” to a varying extent, which sometimes occurs in combination with SST biases in coupled GCMs (Bretherton 2007). The problem may be dealt with by modifying, or tuning, the cumulus parameterization (e.g., Zhang and Mu 2005; Bacmeister et al. 2006; Chikira and Sugiyama 2010).

Bellon and Sobel (2010) investigated this problem by using the Quasi-Equilibrium Tropical Circulation Model (QCTM). They showed that for given equatorially symmetric SST, there exist multiple equilibria: one with an equatorially symmetric rainfall distribution, and the other with an asymmetric (off-equatorial) distribution. They showed that which of the two equilibria tends to be realized depends on subtle settings, such as the parameterized sensitivity of convection to free-tropospheric humidity and the assumed vertical structure of temperature variations.

It is known that the structures like the ITCZ and the Hadley circulation often emerge in aqua-planet experiments even with globally uniform SST (Sumi 1992; Horinouchi and Yoden 1998; Kirtman and Schneider 2000; Chao and Chen 2004; Barsugli 2005). Kirtman
and Schneider (2000) obtained a well-defined ITCZ centered on the equator using an aqua-planet experiment with globally uniform SST. They further conducted an experiment with a coupled oceanic mixed layer model under globally uniform solar insolation. In this case the SST predicted in the model is minimized at the equator, but the ITCZ, though weaker, was formed around the equator.

Barsugli et al. (2005) extended the study of Kirtman and Schneider (2000) and found multiple forms of equilibria depending on the values of the globally uniform solar insolation: an equatorially symmetric double ITCZ, a near symmetric single ITCZ, a transient asymmetric ITCZ, and a stable, strongly asymmetric ITCZ. Hysteresis and multiple equilibria were also found. In their study, asymmetric equilibria were not obtained with their atmosphere-only model with globally uniform SST. However, Chao and Chen (2004) obtained both symmetric and asymmetric ITCZs depending on model settings with prescribed globally uniform SST. Raymond (2000) used a two-dimensional (latitude versus altitude) model and showed that in the presence of the cloud-radiation feedback, an equatorially asymmetric Hadley circulation formed over uniform SST.

The studies introduced above indicate that there is a substantial degree of freedom, at least in numerical models, regarding the structure and the strengths of the ITCZ and the Hadley circulation for given SST. A part of the variety can be attributed to differences in cumulus parameterization, but we do not have a clear theory to explain the variety.

The thermal relaxation in the HH model is often regarded to represent the relaxation toward the radiative-convective equilibrium. However, there is a fundamental difference between a moist convecting and a dry atmosphere in the way temperature adjustment occurs (Emanuel et al. 1994). The high degree of freedom in which how the ITCZ and the Hadley circulation form in numerical models should be attributed to the interactive nature of latent heating to adjust in response to the tropical circulation to form, as demonstrated in this study.

In this study, aqua-planet simulations are conducted to advance our understanding of
the Hadley circulation and the ITCZ for given SST. A special focus is made on the cases conducted using globally uniform SST, where a meridional circulation cannot form under the HH theory. It is shown that the strength of the “Hadley circulation” over the uniform SST varies from being faint to substantial (comparable that in the real atmosphere) as a tunable parameter of the cumulus parameterization of the model is varied. A conceptual two-box model, which is similar to the one by Emanuel et al. (1994), is used to explain this variable nature. It is further shown that convectively coupled waves play an important role in this behavior. The waves affect not only the strength of the circulation but also the fine structure of the simulated ITCZ. Experiments with latitudinally varying SST are also conducted to study the extent to which the mechanisms working in globally uniform SST runs hold.

The rest of the paper is organized as follows. The model and the numerical experiments are introduced in Section 2. Results from the runs using globally uniform SST are presented in Section 3. An investigation is made in Section 4 on thermodynamic constraints using a two-box model. The aqua-planet results are further examined in Section 5 to elucidate possible roles of convectively coupled disturbances. Angular momentum budget is investigated in Section 6. Results using latitudinally dependent SST are investigated in Section 7. Conclusions are drawn in Section 8.

2. Model and experiments

The model used is the CCSR/NIES/FRCGC AGCM version 5.6 (K-1 Model Developers 2004). Numerical experiments are made with the T42 horizontal resolution. The entire surface is assumed to be the ocean with prescribed SST. The number of vertical levels taken is 25, where 19 levels are below the 0.1 sigma level, and the greatest sigma level is 0.0027. The Rayleigh friction is exerted in the stratosphere with the coefficient increasing with altitude up to $30^{-1}$ day$^{-1}$. Analysis is made after interpolating model outputs onto the standard pressure levels.
The cumulus parameterization of the model is the prognostic Arakawa-Schubert scheme, on which an additional constraint is introduced to limit the triggering of deep convection if the sub-cloud relative humidity is under a threshold value \( \text{RH}_C \). The standard setting of \( \text{RH}_C \) is 0.8 (80%). The introduction of \( \text{RH}_C \) to this model improved a bias that the variability of tropical rainfall is too small (Emori et al. 2005). Note that a similar thresholding is introduced in many AGCMs (Gregory and Miller 1989; Sud and Walker 1999; Zhang and Mu 2005; Li et al 2007). In this study \( \text{RH}_C \) is treated as an ad hoc controllable parameter, rather than an object of tuning, to modify the behavior of parameterized convection.

In most experiments, the model’s standard radiation scheme (Nakajima et al. 2000) is used, but the solar insolation is assumed to be steady and globally uniform equal to the annual- and global-mean value. In a series, a simplified 4-color radiation scheme is used. This scheme is not tuned much and is found to cause unrealistically excessive cooling by low-level clouds as much as more than 10 K/day. Therefore, the results obtained with it should not be emphasized much. They are nonetheless shown in this paper, since the results are of some interest from a dynamical point of view.

The vertical eddy diffusion is parameterized by the Mellor-Yamada Level 2 scheme. The horizontal diffusion is on the 8th order \((\propto \nabla^8)\), and the \( e \)-folding time for the greatest total wavenumber of 42 is 1 day.

SST of all the series can be expressed as

\[
\text{SST} = T_0 + \Delta_S (\mu - \mu_0)^2;
\]

(1)

where \( \mu \equiv \sin \phi \), and \( \Delta_S, T_0, \) and \( \mu_0 (= \sin \phi_0) \) are constants. When SST maximizes on the equator \((\mu_0 = 0)\), \( \Delta_S \) is the pole-to-equator SST difference. In many series including the control series, named Cntrl, SST is set to 299 K uniformly over the globe \((T_0 = 299K \text{ and } \Delta_S = 0)\).

The numerical experiments reported are outlined in Table 1. Non-standard settings that have not been described are as follows. In the series AMSI (standing for the annual-mean solar insolation), solar insolation is set to the annual mean value for each latitude. In the
series Eqdmp, the Rayleigh friction with the $e$-folding time of 2 days is exerted on the perturbation horizontal winds (defined as the deviation from the zonal mean) between 10°N and 10°S. In the series Axsym, the axi-symmetric version of the model is used with the same meridional resolution. In the series RotChg, the angular frequency of the planetary rotation $\Omega$ is changed. In other runs, it is set to equal to the Earth’s value $\Omega_E$.

The initial condition of all runs is a resting isothermal atmosphere of 299 K with a small large-scale temperature perturbation, and it was run for 720 days (expressed as 2 years hereafter) or 1440 days (4 years). Although the statistics presented in this paper are made for the 2nd model year, checks were made for the 3rd and 4th years in many cases, and the validity was confirmed.

3. Mean precipitation and circulation when SST is uniform

In the Cntrl series, SST is set uniformly to 299 K, and RH$_C$ is varied. Figure 1 shows the time evolution of the zonal mean precipitation. For RH$_C \geq 0.5$, persistent latitudinal structures emerge spontaneously in the tropics in the 1st year, and they last until the end of the 4th year (not shown). Figure 2 shows precipitation averaged over the 2nd model year. An enhancement in the equatorial region and suppression at higher latitudes in the tropics are found when RH$_C \geq 0.5$, although SST is globally uniform. The equatorial enhancement is called as the “ITCZ” in what follows. Precipitation is nearly globally uniform for RH$_C \leq 0.3$, and a small equatorial maximum is found when RH$_C = 0.4$.

Figure 3 shows the meridional mass stream function $\Psi$ derived numerically based on

$$\overline{v} = \frac{g}{2\pi R_E \cos \phi} \frac{\partial \Psi}{\partial p}, \quad (2)$$

where \(\overline{v}\) is the zonal mean meridional wind, \(g\) is gravity, \(R_E\) is the Earth’s radius, and \(p\) is pressure. Corresponding to the precipitation distribution shown in Fig. 2, circulations like
the Hadley circulation (hereafter simply called as the Hadley circulation or the Hadley cells) form. Its strength at large RH\(_C\) is substantial, being comparable to or greater than the half of the observed climatological mass flux in the equinoxial seasons. The width of each of the Hadley cells is about 20° irrespective of the values of RH\(_C\), which is smaller than that in the real atmosphere. Figure 3 also shows the absolute angular momentum

\[ \bar{m} \equiv R_E \cos \phi (\Omega R_E \cos \phi + \bar{u}), \]

which is investigated in Section 6 (here, \(\bar{u}\) is the zonal mean zonal wind).

These results are similar in the AMSI series, in which latitudinally dependent annual-mean solar insolation is used (not shown). In the AMSI runs, the meridional distribution of mean precipitation has a slightly different \(\phi\) dependence in the extratropics, but the precipitation and the circulation in the tropics are similar to those in the Cntrl runs.

Figure 4 shows the upward mass flux associated with the Hadley circulation in the Cntrl runs (filled squares). The strength of the Hadley circulation is increased as the value of RH\(_C\) is increased from 0 to 0.8 by more than 10 times, and it is slightly decreased when RH\(_C\) is further increased to 0.9. It is noteworthy that altering a tunable parameter of cumulus parameterization (here, RH\(_C\)) can vary the meridional circulation to a large extent in a continuous manner. As mentioned in Section 2, RH\(_C\) modifies the spatiotemporal variability of tropical precipitation, so it is investigated in Section 5. For reference, relative humidity thresholds are introduced in many cumulus parameterizations in the course of GCM tuning [e.g., Sud and Walker (1999) in the relaxed Arakawa-Schubert scheme; Zhang et al (2004) in the Zhang and McFarlane scheme; Li et al. (2007) in the Tiedtke scheme].

Results of the 4-col series are shown in Fig. 5 for RH\(_C\) = 0. The only difference between this and the Cntrl series is in radiation, but the resultant mean precipitation and meridional circulation are very different from the ones shown in Figs. 1a~3a. In the 4-col run, precipitation around 10°S is significantly enhanced, and the corresponding Hadley circulation is asymmetric with a cross-hemispheric mass circulation. The mass flux is comparable to that in the real atmosphere in solstitial seasons, but the width of the circulation is smaller.
The off-equatorial precipitation maximum is due to a persistent tropical cyclone circulating zonally to the west off the equator. The result is similar when $\text{RH}_C = 0.3$, but the tropical cyclone in a hemisphere disappears at 1.3 model year, and at the same time, another appears in the other hemisphere. Therefore, a similar hemispheric flip might occur in the $\text{RH}_C = 0$ run too, if time integration is made further (not done). At higher $\text{RH}_C$ values of 0.7 and 0.9, the tropical cyclone is not formed, and the precipitation is rather equatorially symmetric. The differences between the Cntrl and 4-col runs are interesting. However, the 4-color radiation scheme is not tuned, and low-level cloud causes excessive cooling, so this study mainly focuses on the results obtained with the standard radiation scheme.

Chao and Chen (2004) conducted aqua-planet AGCM simulations with globally uniform SST. The cumulus parameterization used is the relaxed Arakawa-Schubert scheme. They found either equatorially symmetric or asymmetric ITCZ forms depending on model settings such as in radiation (using a simple uniform cooling, or using the model’s radiation scheme with or without clouds), surface sensible and latent heat flux (uniformly prescribed or interactively calculated), and $\text{RH}_C$ (0 or 0.95). Roughly speaking, the meridional distributions of precipitation in the Cntrl runs with large $\text{RH}_C$ are similar to their symmetric cases (although there is a large variation in their results), and those in the 4-col runs with small $\text{RH}_C$ are similar to their asymmetric cases. It is, however, not certain, as it is not mentioned, whether a persistent tropical cyclone is formed in the latter cases of their study.

The contrast between the Cntrl and 4-col experiments is at least superficially consistent with the result by Raymond (2000) by using a two-dimensional model; since the low-level clouds are denser in the subsidence region, the 4-color radiation scheme should have a greater cloud-radiation feedback. This issue is revisited in Section 4. Note, however, that a similar circulation can be obtained with the standard radiation scheme as shown in what follows.

The equatorial precipitation peak in the high $\text{RH}_C$ runs in the Cntrl series is much weaker than those obtained by Horinouchi and Yoden (1998) with the moist convective adjustment scheme and by Kirtman and Schneider (2000) with the relaxed Arakawa-Schubert scheme.
In these studies, the equatorial precipitation was larger than that in the extratropics by a factor of two or more.

In the atmosphere-only experiments by Barsugli et al. (2005), a well-defined equatorially symmetric ITCZ formed with the globally uniform SST values 20°C and 30°C, while the zonal mean precipitation was highly transient and the resultant organization of time-mean precipitation was much weaker when SST was 25°C. The model they used is the NCAR CCM Version 3 (with the physics of the version 3.6.6), so the cumulus parameterization they used must be the Zhang and McFarlane scheme.

In the current study, dependence on the uniform SST is not like what was in Barsugli et al. (2005). As seen in Fig. 4, for RH_C ≥ 0.3, the strength of the Hadley circulation when T_0 = 302 K (≈ 29°C) is quite similar to that when T_0 = 299 K (≈ 26°C). The strength is a little weaker when T_0 = 293 K (≈ 20°C), but the the dependence on RH_C is similar when RH_C ≥ 0.5.

At T_0 = 293 K and RH_C = 0.3, the ITCZ and the Hadley circulation are quite similar to those obtained in the 4-col runs at RH_C = 0 and 0.3. This is the only run with the standard radiation scheme in which a distinct asymmetric circulation is formed. However, there could be multiple equilibria for some parameter values, which is not investigated in this study.

4. Thermodynamic constraints

The results shown above, along with the past studies mentioned above, suggest that the strength of the ITCZ and Hadley circulation is quite variable and depends on subtle model setups such as a tunable parameter in the cumulus parameterization. The existence of the circulation cannot be explained by the HH theory.

Here, thermodynamic constraints on the tropical meridional circulation and precipitation are examined using a conceptual two-box model illustrated in Fig. 6. The model is similar to the one used by Emanuel et al. (1994) to discuss the Hadley circulation, but it is simplified
further to focus on the fundamentals of thermodynamic energy budget across the boxes.

If the horizontal transport of dry static energy \( s \) is neglected, which can be justified to the first approximation in the tropical free troposphere (Sobel et al. 2001), and if surface sensible heating neglected as being small, the steady state thermodynamic energy equation of the boxes can be approximated by

\[
-\sigma \omega_u = Q_{ru} + C_u, \quad (4)
\]
\[
-\sigma \omega_d = Q_{rd} + C_d, \quad (5)
\]

where subscripts \( u \) and \( d \) represent the values of the boxes U and D, respectively, \( \omega \) is the column-mean pressure velocity, \( \sigma \) is a positive parameter on the static stability, which is equal to \( -\frac{\partial s}{\partial p} \) if it is vertically constant, and \( Q_r \) and \( C \) are the column-mean radiative and condensation heating, respectively.

Under the persistent presence of penetrative deep convection somewhere in the boxes (or a box), the temperature profiles of both boxes approach to the moist adiabat. Thus, the radiative heating rate can be approximated as \( Q_{ru} = Q_{rd} = -R_0 \), where \( R_0 \) is a constant radiative cooling rate. Then, by combining Eqs.(4), (5), and the continuity equation

\[
l_u \omega_u + l_d \omega_d = 0, \quad (6)
\]

and using \( C_d \geq 0 \), the following relations can be obtained:

\[
\omega_d \leq \sigma^{-1} R_0, \quad (7)
\]
\[
\omega_u \geq -\frac{l_d}{l_u} \sigma^{-1} R_0, \quad (8)
\]
\[
C_u \leq \frac{l_u + l_d}{l_u} R_0. \quad (9)
\]

Equation (7) shows the obvious fact that the downward motion in the box D is limited by the radiative cooling rate. The upward motion in the box U is related to that as Eq.(8) through the mass conservation Eq.(6). Within the limitation imposed by radiation, the values of \( C_u \) and \( C_d \) are adjustable depending on the circulation formed.
Condensation heating must satisfy the steady state moisture budget. However, horizontal transport can play a significant role in the momentum budget, especially when eddy transport is available. Thus, introducing a moisture budget equation would introduce a new variable, so it does not necessarily impose an effective constraint on the relation between the circulation and condensation heating.

The cloud-radiation feedback can be crudely expressed by setting $Q_{ri} = -R_0 + rC_i$ [here, $i = d, u$; and $r (\ll 1)$ is a positive constant (e.g., Bretherton and Sobel 2002)]. In this case, it is only to replace $C_i$ above with $(1+r)C_i$. Therefore, the feedback only enhances the effect of $C_i$, or, in other words, it is only to decrease the strength of $C_i$ needed to achieve a balance. Although the contrast between $Q_{rd}$ and $Q_{ru}$ is in the sense to enhance the circulation, its role is passive. Note, however, that if pursuit is made with a two-box model to self-consistently predict the equilibrium, which is out of the current scope, the box dimensions may be changed if a new process such as the cloud-radiation feedback is introduced (Bretherton and Sobel 2002).

The ratio between $C_u$ and $C_d$ has been left as a free parameter. Its variety depending on factors such as cumulus parameterization indicates that it is indeed a free parameter at least when SST is uniform. This is the fundamental reason that a meridional circulation is possible when SST is globally uniform.

Note that $C$ is the net condensation heating in atmospheric columns. It is zero in the dry convective adjustment. That is, the argument above is applicable to the radiative-convective atmosphere in which net latent heating occurs. Note also that the thermodynamic constraints from the angular momentum budget proposed by HH is on vertical averages, since it constrains the thermal-wind-balanced temperature obtained by contrasting the upper branch and the surface. Therefore, the thermodynamic framework of HH is applicable to a dry radiative-convective atmosphere. That is, the HH theory may be applicable to other planets such as the Mars, although the role of eddies has to be considered.

The effect of non-uniform SST is the subject of Section 7. Here, the problem is visited
briefly in the context of the two-box model. SST strongly affects mixing layer temperature, so it affects the convective available potential energy of the boxes. Therefore, although sensible heating is small compared with $Q_r$ and $C$, SST can significantly affect the ratio between $C_u$ and $C_d$ through its control on the sub-cloud moist static energy. The SST control could be perfect if there is no sub-box variability. However, cumulus convection is fundamentally a sub-box phenomenon. The next section shows that transient variability plays an important role in the simulated Hadley circulation. Then it is of interest to what extent the same mechanism works when SST is not uniform (Section 7).

5. Possible role of convectively coupled disturbances

The discussion in Section 4 suggests that a concentration of precipitation to induce a large-scale circulation is not impossible even when SST is uniform, but it does not tell what determines the strength and the structure. In this section, it is shown that a key is in the spatiotemporal variability of simulated convection and dynamical disturbances.

a. Control runs

Figure 7 shows longitude-time plots of tropical precipitation in the Cntrl series runs. Variability is larger at RH$_C$ $\geq$ 0.5, at which well-defined Hadley circulations are formed, than at smaller RH$_C$ values. Both eastward- and westward-propagating signals are seen there. At RH$_C$ is increased from 0.7 to 0.9, the zonal scales of disturbances become smaller.

Figure 8 shows zonal wavenumber-frequency spectra of tropical precipitation. Signals are enhanced along the dispersion curves of the equatorial waves at the equivalent depth $h$ around 30 m when RH$_C$ $\geq$ 0.5. This feature indicates the existence of convectively coupled equatorial waves (Takayabu 1994; Wheeler and Kiladis 1999). Signals corresponding to Kelvin waves and the mixed Rossby-gravity (MRG) waves (or the $n = 0$ eastward-moving inertia gravity waves, which are not distinguished from the MRG waves in this study) are especially evident,
while it is difficult to distinguish simple advection and Rossby-wave signature from this figure. A similar spectral feature was obtained by Horinouchi and Yoden (1998) in an aqua-planet experiment with globally uniform SST.

If a large fraction of tropical precipitation is associated with convectively coupled equatorial waves, it will produce meridional contrast in the distribution of mean precipitation. If averaged over the cycles of waves, convergence and divergence would cancel, but precipitation would not, since it is a nonlinear positive-only quantity. Convergence and divergence associated with low equatorial wave modes occur predominantly near the equator. If \( h = 30 \text{ m} \), the equatorial radius of deformation \( l_e \) is 870 km. In the Kelvin waves, convergence and divergence peak at the equator, and the strength falls to \( e^{-1/2} \) times at \( |y| = l_e \), where \( y \equiv R_E \phi \) is the distance from the equator; convergence and divergence of the MRG waves peak at \( |y| = l_e \); in the \( n=1 \) Rossby waves, the peaks are at \( |y| \leq l_e \), but the meridional tails are slightly wider than that of MRG waves. Therefore, the enhancement of precipitation at \( y \lesssim 1.5 \) seen in Fig. 2 is consistent with the enhancement by convectively coupled equatorial waves.

If precipitation is enhanced in the equatorial region for some reason, precipitation at higher latitudes in the tropics can be suppressed by the formation of subsidence as discussed in Section 4. The equatorial concentration of precipitation can occur for other reasons, which do not necessarily require zonal asymmetry. However, the following results suggest that equatorial disturbances do play important roles in the simulated ITCZ and Hadley circulation.

Figure 9 shows the relation between lower-tropospheric perturbation kinetic energy, where perturbation means deviation from the zonal mean, and the upward mass flux of the Hadley circulation shown in Fig. 4. Although there is no clear causal relationship between them, the relationship is remarkably compact, perhaps too compact by coincidence. The slope obtained by the least-square fit is 1.19. The relation is rather insensitive to small changes in the latitudinal widths and the vertical extent over which the kinetic energy is averaged.
If the energy is calculated for the upper troposphere, the relationship is still similar, but it is slightly less compact and the slope is higher (1.39 for $200 < p < 600$ hPa).

This result supports, though it does not prove, the suggestion that the convectively coupled equatorial waves play an important role to determine the strength of the simulated Hadley circulation. Note that the circulation is thermally direct, having upwelling where latent heat is released. Therefore, the circulation is not wave-driven.

Convectively coupled equatorial waves play a further role to determine the fine structure of the tropical zonal mean precipitation. Figure 2d shows that tropical precipitation is enhanced right at the equator (actually on the 2 grid points straddling the equator) when $R_{HC} = 0.5$. Figure 8dl suggests that when $R_{HC} = 0.5$, convectively-coupled Kelvin waves are significant, but convectively-coupled MRG waves are weak. This feature is consistent with the narrow peak at the equator. When $R_{HC}$ is 0.6~0.8, on the other hand, the tropical precipitation is enhanced over a wider latitudinal range, and secondary peaks are found at the grid points at $|\phi| \sim 7^\circ$ (Fig. 2). In this $R_{HC}$ range, both the Kelvin and the MRG waves are significant (Fig. 8). This is also consistent with the distribution of tropical precipitation. When $R_{HC} = 0.9$, the signature of MRG waves is also evident, and slow westward-moving spectral power, which might be partly associated with Rossby waves, is relatively strong. This feature could be consistent with the tropical precipitation structure in Fig. 2h, which is smoother than that with smaller $R_{HC}$ values.

b. Restricting equatorial disturbances

Further investigation is made to elucidate the possible roles of convectively coupled equatorial waves. Figure 10 shows the mean precipitation and mass stream function from the Eqdmp run. In this run, the Rayleigh friction with the time scale of 2 days is applied to the perturbation horizontal winds between $10^\circ$N and $10^\circ$S. The resultant Hadley circulation is weaker and the contrast in the tropical precipitation is smaller than in the corresponding Cntrl run with $R_{HC} = 0.7$. This is expected if convectively coupled equatorial waves play
important roles in the formation the Hadley circulation in the Cntrl run. However, precipitation minima still exist around $|\phi| \sim 20^\circ$, and the Hadley circulation did not vanish. In this run, equatorial precipitation varied nearly axi-symmetrically, but transient disturbances did not disappear. The dominant variation is a zonal-wavenumber 0, equatorially antisymmetric oscillation with a period of 4 days, as can be seen in Fig. 10a at a close look. The oscillation is consistent with the zonal wavenumber zero MRG wave with $h \sim 20$ m. It is not clear to what extent the subtropical weak rainfall suppression can be attributed to the transient disturbances.

Figure 11 shows the result from the Axsym run. The mean precipitation shows narrow peaks and depressions around the two tropics (Fig. 11c). The meridional stream function shows corresponding narrow peaks (11b). Note that transient variability is evident in this run too (11a). Kirtman and Schneider (2000) showed that transient variability dominates the momentum transport in the tropical lower troposphere in their axi-symmetric run, although the variability is at much lower frequencies than in the present study. See also Satoh (1995) for axi-symmetric aqua-planet experiments.

Axi-symmetric runs exclude not only convectively-coupled non-zero wavenumber waves but also other disturbances that can redistribute angular momentum. Therefore, to investigate this run is not very fruitful in the current context of the study. Section 6 will make it more evident.

c. Changing the rotation rate

In the RotChg series, the planetary rotation rate is changed to $\frac{1}{2}$ and $\frac{1}{4}$ times as the Earth’s rotation rate. The resultant time evolution of zonal mean precipitation is shown in Fig. 12. The width of enhanced precipitation in the ITCZ is approximately doubled when the rotation rate is 4 times slower. This result is consistent with the change in $l_e$, which is proportional to $\Omega^{-1/2}$. Thus, the result is not inconsistent with the importance of convectively coupled equatorial waves.
However, there could be other factors that also vary in proportion to $\Omega^{-1/2}$. For instance, the critical latitude at which the baroclinic instability shown in the next section is initiated can also be proportional to $\Omega^{-1/2}$ in the equatorial $\beta$ plane. Also, when dealing with such scaling lows, one should be aware of possible limitation of the equatorial $\beta$-plane approximation. Its validity is a prerequisite for a simple meridional scaling low to hold. This may not be granted if the phenomena of interest extend well into the extratropics.

6. Angular momentum budget

Meridional temperature structure is associated with zonal wind through the thermal wind relationship. HH showed that if the absolute angular momentum around the Earth’s rotation axis is conserved along the poleward branch of the Hadley circulation, vertically averaged temperature decreases with latitude in proportion to $y^4$. If SST is uniform, atmospheric temperature near surface is also nearly uniform. In this case, the static stability would decrease with latitude, since temperature aloft must decrease to accomplish the decrease in the vertical mean. Therefore, if the circulation is axi-symmetric and nearly invicid, there exists a negative feedback in the moist atmosphere to suppress the formation of the (at least near-symmetric) ITCZ.

In the Cntrl runs, however, the angular momentum is not conserved along the poleward branch of the Hadley circulation, as shown in Fig. 3. Actually, zonal wind is quite weak as shown in Fig. 13, so the angular momentum is dominated by the planetary rotation.

Is the angular momentum change along the upper branch induced by the convectively coupled equatorial waves? If the answer is yes, one can say that the simulated Hadley circulation is created self-consistently by the waves. However, the answer is no, as shown in what follows.

The steady state angular momentum budget is expressed in the standard notation of the
log-pressure coordinate system (see Andrews et al. 1987) as

\[ \bar{v} \frac{\partial \bar{m}}{\partial \phi} + \bar{w} \frac{\partial \bar{m}}{\partial z} = \rho_{0}^{-1} \nabla \cdot \bar{F} + \bar{X}. \]  

(10)

Thus, the angular momentum change along meridional circulation is associated with the divergence of the Eliassen-Palm (EP) flux \( \bar{F} \). The frictional term \( \bar{X} \) is negligible in the free troposphere. Here, \( \bar{v}^* \) and \( \bar{w}^* \) are the transformed Eulerian mean residual circulation rather than the naive Eulerian mean circulation shown in Fig. 3. However, it is confirmed for the Cntrl runs that the difference is small in the Hadley circulation region (not shown). On the other hand, the simulated “Ferrel” circulation is rather stronger in the residual circulation than in Eulerian circulation, suggesting that the direction of the meridional Stokes drift is opposite to that in the real atmosphere.

The EP flux and its divergence in the Cntrl runs are shown in Fig. 14. A convergence (in bluish colors) is found in the upper troposphere within the Hadley circulation. This is consistent with the angular momentum decrease along the poleward branch. The EP flux that caused this convergence comes from higher latitudes. A further analysis (not shown) is made to confirm that the flux is associated with intrinsically westward-moving disturbances, so the direction of arrows represents that of the group propagation.

The EP flux from higher latitudes (at around 30°) is likely due to baroclinic instability. The mechanism is illustrated in Fig. 15. Without contributions from eddies, steady-state thermal-wind-balanced zonal wind outside the meridional circulation is zero, if SST and solar insolation are uniform. Therefore, if the upper branch of the meridional circulation conserves the angular momentum, a shear (or a discontinuity in zonal wind if the system is invicid) will develop at the poleward boundary of the circulation. The shear is cyclonic, so the potential vorticity there has a positive anomaly. If it is strong enough, the meridional potential vorticity gradient is negative on its poleward flank. Therefore, it is unstable to cause stirring. This mechanism is essentially barotropic, but since it occurs in a limited vertical range, the resultant disturbances are more or less baroclinic. The actual latitudes at which the unstable disturbances develop in simulations depend on the zonal wind at the
equator \((u_{eq})\) and the model’s resolution. It was confirmed that the contribution of the model’s horizontal hyper-diffusion was negligible.

The mechanism proposed above is passive to the meridional circulation. Thus, it is understood that the EP flux convergence/divergence was the larger in the runs in which the meridional circulation was the stronger. Also, this mechanism does not occur in axi-symmetric runs. Therefore, there is a fundamental difference between the Eqdmp and Axsym runs.

7. Effect of non-uniform SST

The importance of convectively coupled equatorial waves was as shown in Section 5 using the experiments with globally uniform SST. This feature is dynamically supported by the high-degree of freedom in the meridional distribution of convective heating as shown in Section 4 and the passive angular momentum redistribution shown in Section 6. However, the occurrence of penetrative convection is affected by gross moist stability. It depends on sub-cloud moist static energy, which is affected, if not dominated, by SST. Therefore, it is questioned to what extent the mechanisms working in the uniform SST experiments work, if SST is not uniform.

As mentioned in Section 1, Kirtman and Schneider (2000) obtained an ITCZ situated around the equator even when SST, which is interactively predicted in a coupled oceanic mixed layer model, is minimized there. This result indicates that SST does not exclusively dominate the ITCZ and the meridional circulation by at least in numerical models. Here, investigation is made on the effect of SST variation by introducing a simple meridional dependence decreasing toward the poles.

Figure 16 shows the meridional distribution of precipitation obtained in the Y2-eq and Y2-10N series. As \(\Delta_S\) is increased, precipitation around the SST peak is increased. At the same time, the width of suppressed region, which is associated with subsidence, is increased.
The increase in the poleward extent of the subsidence region may be explained by the poleward shift of the baroclinic instability suggested in Section 6. This is because the local thermal wind outside the meridional circulation is increased as the meridional SST gradient is increased. Also, there may be contributions from the well-known baroclinic instability in which the baroclinicity at the surface plays an essential role.

At $\Delta S = 40$ K, the overall feature of the ITCZ and the subtropical precipitation minima are similar between the cases with $RH_C = 0$ and 0.7, for both Y2-eq and Y2-10N series. Figure 17 shows that both the Hadley circulation strength and the lower tropospheric eddy kinetic energy is insensitive to $RH_C$ when $\Delta S = 40$ K.

When $\Delta S \leq 20$ K, both the Hadley circulation strength and the eddy kinetic energy have a dependence on $RH_C$. The two are positively correlated as seen in Fig. 17. Therefore, the importance of transient disturbances found in $\Delta S = 0$ runs appears to remain when $\Delta S \neq 0$. However, as $\Delta S$ is increased, the sensitivity to $RH_C$ values is decreased, and it vanishes at $\Delta S = 40$. Also, the compactness of the relation appears to deteriorate. Therefore, it is difficult to quantify the role of transient disturbances or convectively coupled equatorial waves only from the experiments conducted in this study.

The convectively coupled equatorial waves, however, leave clear signatures in the fine structures of the simulated ITCZs even when $\Delta S$ is not zero. As in the cases with $\Delta S = 0$ described in Section 5, some of the simulated ITCZ (when $\Delta S \neq 0$) have equatorial sharp peaks, while some have peaks off the equator. Zonal wavenumber-frequency spectra of tropical precipitation as shown in Fig. 8 are examined for non-zero $\Delta S$ (figures now shown), and it is found that the correspondence between the ITCZ structure and the dominant convectively coupled equatorial wave signals hold even when $\Delta S > 0$. More specifically, for both series, when $\Delta S = 5$, 10, or 20 K, the MRG wave signals are weak if $RH_C = 0$ and are evident when $RH_C = 0.7$. As for the cases with $\Delta S = 40$ K, a clear explanation was not found, but for both $RH_C = 0$ and 0.7, low-frequency westward signals exhibited relatively high power, so this could explain the meridional structures.
It is noteworthy that in the Y2-10N series the meridional distribution of precipitation does not follow the SST increase in the northern hemisphere. The maximum is in the southern hemisphere up to $\Delta s = 20$ K when $RH_C = 0.7$. This behavior may be supported by the convectively coupled equatorial waves. Note that precipitation is suppressed in the “winter” hemisphere more heavily than in the other hemisphere even at the lowest non-zero $\Delta s$. This hemispheric contrast in subsidence can be explained in terms of the readiness to accomplish angular momentum transport (Lindzen and Hou 1988).

8. Summary and conclusions

Aqua-planet simulations are conducted to advance the understanding and numerical modeling of the Hadley circulation and the ITCZ for given SST. A special focus is made on the cases conducted with globally uniform SST.

In the control series, SST is set uniformly to 299 K, and the relative humidity threshold of the model’s cumulus parameterization, $RH_C$, is varied. Depending on the threshold value, features like the ITCZ and the Hadley circulation that are nearly symmetric with respect to the equator emerge spontaneously. The strength of the circulation is increased as the value of $RH_C$ is increased from 0 to 0.8 by more than 10 times, and it is slightly decreased when $RH_C$ is further increased to 0.9. The largest strength is greater than the half of the observed climatological mass flux in the real atmosphere in the equinoctial seasons. The width of each of the Hadley cells is about 20° irrespective of the values of $RH_C$, which is smaller than in the real atmosphere. When the radiation scheme is changed to a simple 4-color scheme, which causes excessive cooling by low-level clouds, and when $RH_C$ is small, an equatorially asymmetric Hadley circulation is obtained. This circulation is associated with a long-lived tropical cyclone. A similar case is found with the standard radiation scheme, when the prescribed uniform SST is 293 K and $RH_C = 0.3$.

These results, along with past studies, suggest that the strength of the simulated ITCZ
and Hadley circulation is quite variable and depends on subtle model setups such as a tunable parameter in cumulus parameterization. By using a conceptual two-box model, it is shown that in an atmosphere in which convection releases net latent heat release, the distribution of convective heating can be interactively adjusted while a circulation is formed. The cloud-radiation feedback does not affect the picture qualitatively. Thus, miscellaneous factors such as the convectively coupled equatorial waves can affect the ITCZ and the Hadley circulation. Also, it is indicated that if latent heating can be neglected, which may be possible on other planets, the thermodynamic framework of HH may be applicable to radiative-convective atmosphere, although the roles of eddies has to be considered.

In the control series, the spatiotemporal variability of tropical precipitation is large in the runs with large RH$_C \geq 0.5$, in which well-defined ITCZs and Hadley circulations formed. In this case, space-time spectra of tropical precipitation exhibited clear signatures of convectively coupled equatorial waves whose equivalent depths $h$ are around 30 m.

The wave can cause the concentration of precipitation to the equatorial region. If averaged over the cycles of waves, convergence and divergence would cancel, but precipitation would not, since it is a nonlinear positive-only quantity. The meridional scales of the low equatorial wave modes of $h \sim 30$ m are consistent with the meridional extent of the enhanced precipitation. Moreover, the fine structure of the ITCZ in each run is consistent with the meridional structure of convergence field associated with dominant equatorial waves. It is found that the strength of the simulated Hadley circulation has a high correlation with the eddy kinetic energy in the tropical lower troposphere. If an additional Rayleigh dumping is introduced on perturbation horizontal winds in the equatorial regions, the Hadley circulation was weakened. If the planetary rotation rate is changed to 4 times slower, the width of enhanced precipitation in the ITCZ is approximately doubled, which is consistent with the $\Omega$ dependence of the equatorial radius of deformation. These results suggest the importance of convectively coupled equatorial waves in the simulated ITCZ and Hadley circulation.

If the poleward branch of the circulation conserves the angular momentum around the
rotation axis, a negative feedback exists to suppress the formation of ITCZ, since the thermal wind balance implies that the static stability is decreased as the distance from the equator is increased. However, the angular momentum is effectively reduced while being advected in the poleward branch, so the feedback does not work. It is accomplished by baroclinic (or possibly barotropic) instability within the upper troposphere.

Simulations are also conducted with SST decreasing toward the poles, where the pole-to-equator SST difference is characterized by the parameter $\Delta S$. As $\Delta S$ is increased for given RH$_C$, precipitation is more concentrated to around the SST peaks, and the meridional circulation is strengthened, as expected in terms of the SST control on the Hadley circulation. For given $\Delta S$, however, there still remains a tendency that the circulation is the stronger if the lower-tropospheric eddy kinetic energy is the greater. Therefore, the convectively coupled waves are likely to play a role in the runs with non-uniform SST. However, as $\Delta S$ is increased, the sensitivity to RH$_C$ values is decreased, and it is vanished at $\Delta S = 40$. Thus, it is difficult to quantify the role of transient disturbances only from the numerical experiments conducted in this study. Nonetheless, the fine structures of the ITCZs are consistent with the meridional structure of the dominant equatorial waves when $\Delta S > 0$ too.

This study shows that SST does not necessarily dominate the ITCZ and the Hadley circulation when SST gradient is weak. Convectively coupled equatorial waves affect the concentration of precipitation to the equatorial region and furthermore the internal structure of ITCZ. Their roles have not drawn much attention in the context of the climatology of the ITCZ and the Hadley circulation. However, they might be important in the real atmosphere, and also they can affect climate predictions by numerical modelling. In numerical models, the waves are greatly affected by cumulus parameterization. For better climate modeling and understanding, further studies would be needed to establish the relationship among cumulus parameterization, transient disturbances, and tropical circulation.
Acknowledgments.

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<td>$\phi_0 = 10^\circ$N</td>
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As in Fig. 5 but for the Axsym run.

As in Fig. 1 but for the RotChg series.

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