The Effect of Parameterizing Convection on the Steady Large-Scale Tropical Circulation of an Aqua Planet

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RESUMEN

Se ha iniciado un estudio sobre el mantenimiento y la dinámica de las Zonas de Convergencia Intertropical (ITCZ) mediante la aplicación de un modelo de Circulación General de la atmósfera, ya que la dinámica y energía de los procesos que mantienen a tales zonas no se conocen suficientemente, a pesar de su gran importancia. En este artículo se analiza la forma en que el esquema utilizado para parametrizar la información de cúmulos afecta a la situación de las ITCZ y a la circulación tropical a gran escala. Se han realizado una serie de experimentos con un Modelo de Circulación General, en el que se supone que el borde inferior es agua con una temperatua superficial (SST) fija, es decir, un «planeta acuoso». Todos los experimentos se realizaron bajo condiciones equinocciales sin variación zonal de la SST, utilizando dos esquemas diferentes para parametrizar la convección (esquema Kuo y de «ajuste convectivo húmedo»).

De los resultados obtenidos se deduce que la situación de las ITCZ es sensible a los esquemas de convección y a la distribución de la SST. El modelo con un esquema de «ajuste convectivo húmedo» siempre sitúa las ITCZ sobre el máximo de SST, incluso con un débil gradiente de la SST. Por contra, el modelo con un esquema Kuo no es tan sensible a la distribución de la SST, observándose que, con una gran variedad de distribuciones de SST, incluyendo el caso en que la máxima SST está sobre el ecuador, las dos ITCZ se localizan siempre a 7° de latitud a ambos lados del ecuador. La repercusión global de este comportamiento es notable, ya que la situación de las ITCZ afecta a la estructura e intensidad de las células de Hadley, en promedio

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temporal, de las corrientes en chorro subtropicales y de la circulación tropical a gran escala.

ABSTRACT

We have initiated a study of the maintenance and dynamics of the Intertropical Convergence Zones (ITCZs) using a General Circulation Model of the atmosphere. The dynamics and energetics of the processes maintaining the ITCZs are poorly understood despite the fact that they are such a prominent feature in the general circulation of the atmosphere. In this paper, we explore how the cumulus adjustment process affects the location of the ITCZs and the large-escale tropical circulation. We report on a series of experiments with a general circulation model of an aqua planet where the lower boundary is specified to be water at a fixed sea surface temperature (SST). All experiments are run using equinoctal conditions with no *longitudinal* variation in SST. Two different convective parameterization schemes (Kuo and moist convective adjustment) and several different zonally symmetric SST distributions are used in these experiments.

We find that the location of the ITCZ is sensitive to the convective parameterization scheme and the SST distribution. The model with the moist convective adjustment scheme always produces an ITCZ over the tropical SST maximum, even under conditions where the SST gradient is weak. By contrast, the model with the Kuo convective parameterization is not as sensitive to SST distribution. The model with the Kuo scheme yields two ITCZs straddling the equator at approximately 7° latitude for a wide variety of SST distributions, including when the warmet water is located on the equator. The location of the ITCZ affects the structure and strength of both the time mean Hadley cells and the subtropical jets, as well as the large-scale tropical circulation.

1. INTRODUCTION

The Intertropical Convergence Zones (ITCZs) are prominent features of the earth's atmosphere. They appear in satellite photographs as bands of clouds on the order of a few degrees of latitude in thickness, roughly aligned in the east-west direction. The ITCZs over land tend to follow the seasonal march of the sun. However, over the Pacific Ocean there is a distinct precipitation minimum over the equator during all seasons (Taylor, 1973; Jaeger, 1976) with the ITCZ generally located north of the equator. ITCZ are inherently related to the thermally direct Hadley circulation in the tropics. The latter circulation must exist in the tropics because there is insufficient angular momentum provided by the curvature of the Earth to balance a radiative equilibrium wind profile (Schneider, 1977, 1984; Held and Hou, 1980; Dunkerton, 1989). Moreover, in a moist atmosphere the upward branch of the Hadley Cell should manifest itself as a thin zone of cumulus towers the ITCZ. Hence, the ITCZ are intimately involved in determining the global atmospheric circulation.

There is a propensity for the observed ITCZ to occur over the warmest sea surface tamperature (SST) (Saha, 1971). In figure 1 we have displayed the «meridional sea surface temperature differences» (SSTD) across the equatorial Pacific Ocean for the March-June season, with the location of the climatological maximum in rainfall (i.e., the ITCZ) for March to May superposed. Here, SSTD is defined as SST less SST on the equator *along a line of constant meridian.* The SSTD indicates the streng and direction of meridional SST gradient averaged between any location and the equator. A careful examination of the observation plotted in figure 1 indicates that it is not solely the SST that determines the position of the ITCZ. In the Pacific the ITCZ tends to be located in the Northern Hemisphere even when the highest SSTs are situated south of the equator. Additionally, there is a rather large area in the central Pacific where the gradients are weak, yet the ITCZ is found off and well to the north of the equator (fig. 1). Also, note that in the western Pacific the SST is a maximum on the equator, yet the maximum in precipitation is still sharply confined and is located off the equator (see also, Jaeger, 1976).

Modelling studies of the ITCZ have been done with both two-dimensional axisymmetric models and general circulation models. The axisymmetric

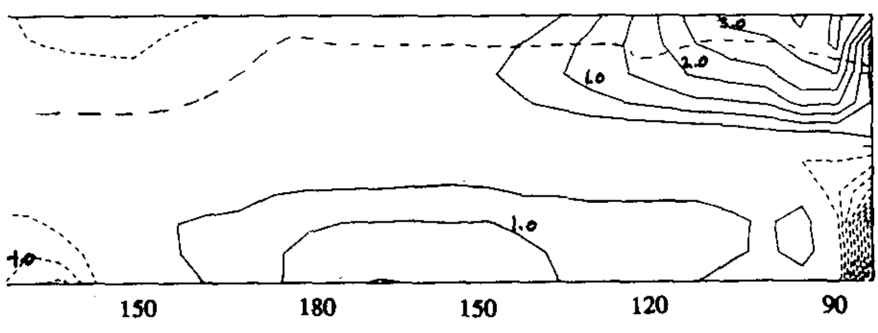

Figure 1.—A contour plot of the equatorial Pacific Ocean «meridional sea surface temperature differences» (SSTD) across the equatorial Pacific Ocean for the March-June season. Here, SSTD is defined as SST less SST on the equator *along a line of consant meridian.* Inasmuch, SSTD indicates the strength and direction of meridional SST gradient averaged between any location and the equator. Hence, negative values flanking the equator indicate a SST maximum near the equator, while positive values north of the equator in conjunction with negative values south of the equator indicate a «large-scale» meridional SST gradient with warmer water north of the equator and colder water south of the equator. The location of the climatological maximum in rainfall (i.e., the ITCZ) for March to May is indicated by a heavy dashed line. The plot is produced using the averaged March and April SST from COADS and the precipitation estimates from Dorman and Bourke (1979). The contour interval is 0.5°C and positive (negative) contours are solid (dashed).

models presented in Pike (1971), Schneider (1977) and Goswami *et al.* (1984) always produce precipitation maxima over the SST maximum. Pike's study is unusual in that he couples an axially symmetric atmospheric model to an axially symmetric ocean model, whereby cold water is produced along the equator by upwelling and the ITCZ is forced off the equator.

The studies of Charney (1966, 1973) and Holton *et al.* (1971) suggest that off-equatorial ITCZs may exist with maximum SST on the equator due to processes inherent to the atmosphere. Charney argues that the structure and dynamics of the ITCZ's are governed by conditional instability of the second kind (CISK), where moisture convergence is maintained by boundary layer pumping. Charney argues that the position of the ITCZ is determined by a steady balance between the supply of moist static energy, decreasing from the equator to the pole, and Ekman layer convergence which increases with the Coriolis parameter. However, Charney's hypothesis is questioned by Schneider and Lindzen (1977).

Holton *et al.* (1971) discuss a singularity in the Ekman layer equations or zonally propagating waves (wave-CISK). The maximum boundary layer convergence associated with these waves occurs at a critical latitude where the local Coriolis frequency equals the frequency of the wave. Holton *et al.* (1971) note the 4-5 day easterly waves observed in the tropical eastern Pacific (Wallace and Chang, 1969) should achieve maximum fueling from wave-CISK Ekman pumping at a critical latitude of about 6° and, in a time average, be manifest as an ITCZ (or, in an axially symmetric atmosphere, two ITCZs paralleling the equator at about 6° latitude). While Holton *et al.* (1971) suggest the observed off-equatorial ITCZZ in the Pacific may be wave induced, they point out the cause and effect is not clear. Charney (1973), on the other hand, suggests it is a preexisting ITCZ which sets the vertical and horizontal scales of the waves.

Recently, the question of what determines the position of the ITCZ has resurfaced in connection with atmospheric models. Hayashi and Sumi (1986) run a general circulation model (GCM) with the lower boundary condition set to a global ocean surface (an aqua planet) with zonally and hemispherically symmetric sea surface temperatures monotonically decreasing from the equator. They find two ITCZ's straddling the equator even though the SST maximum is prescribed to be on the equator. Swinbank *et al.* (1988) repeat Hayashi and Sumi's aqua planet experiment using the ECMWF GCM, and also report twin ITCZs flanking the equator. However, Lau *et al.* (1988), in a similar aqua planet experiment with the GFDL GCM, find one ITCZ on the equator. In their case, the sea surface temperature is determined by the condition that there is no net average energy flux through the lower boundary. Lau *et al.* (1988, Appendix A) suggest that their GFDL aqua planet simulation obtains one ITCZ, in contrast to the other studies, due to differences in surface energy fluxes that arise from the different SST boundary conditions.

Thus, over an ocean with SST maximized on the equator there still seems to be some question whether the atmosphere favors a single ITCZ centered on the equator, as suggested by the axisymmetric theory and calculations, or two ITCZs paralleling the equator as suggested by Charney (1966) or Holton *et al.* (1971). We have run a set of experiments with a GCM in an aqua planet configuration to examine the processes that determine the position and maintenance of the ITCZ. We chose an aqua planet configuration so as to avoid the complicating effects of orography and land-mass heating on the location of the ITCZs. With one exception, the set of experiments described in this paper feature changes in only the prescribed SST and the parameterization scheme for convection. The maximum solar radiation is directly over the equator in perpetual March 21 conditions in all experiments.

The paper is organized as follows: In section 2 we give a brief description of the model used and the convective parameterization schemes implemented in it. We summarize in Section 3 the various experiments and the distinguishing characteristics of each experiment. We examine the effect of the location of the ITCZ on the large-scale circulation in Section 4, and present our conclusions and a discussion of the results in Section 5. The reader is referred to a companion paper, submitted to *Journal of Atmospheric Sciences,* for an extended analysis of the experiments discussed in this paper.

2. THE GENERAL CIRCULATION MODEL

2.1. Description of the model

The global general circulation used in this study is the NCAR Community Climate Model-1 (hereafter, CCM) and is described in Williamson *et al.* (1987). The radiation package for the model is described in Kiehl *et al.* (1987). At the surface a bulk aerodynamic parameterization is used to specify the fluxes of heat, momentum and moisture; the parameterization of the planetary boundary layer follows Deardorff (1972). All of the experiments are performed at T42, affording a horizontal resolution at the equator of approximately 2.8° by 2.8°. There are 12 layers in the vertical.

2.2. Description of the Convective Schemes

One of two different convective parameterization schemes is used in each of the experiments we have run: the moist convective adjustment scheme or a modified Kuo scheme. The moist convective adjustment (MCA) scheme used in the CCM is described in Williamson *et al.* (1987) and is based on the work of Manabe *et al.* (1965). This scheme adjusts a moist, unstable column of air to the moist adiabatic lapse rate. Relative humidities that exceed saturation due to the large-scale motions and moist convective adjustment are adjusted to 100 %, with the excess water vapor instantly rained out.

The basis of the Kuo parameterization used in our experiments follows from the work of Kuo (1965, 1974), Anthes (1977), Donner *et al.*

(1982) and Krishnamurti *et al.* (1983). Briefly, the precipitation is assumed to be proportional to the moisture convergence in the column. A simple «plume type» steady state cloud model predicts in-cloud properties and mass fluxes. The closure assumption of the parameterization determines the rainfal rate within the grid box (determined buy the Kuo «b» parameter). The plume model also predicts a rainfall rate (determined by a Kessler type microphysical parameterization). The ratio of the two rainfall rates is assumed to define the fractional area occupied by the clouds within the grid box. Non-hidrostatic effects and pressure differences between cloud and environment are incorporated in the present scheme following Donner *et al.* (1982), as are the closure assumptions for the «b» parameter suggested by Krishnamurti *et al.* (1983). Some additional constraints are included to identify instances where environmetal conditions are clearly not suited for convection and to enforce mass and energy conservation.

We note that both the Kuo and moist convective adjustment schemes affect the potential energy of the atmosphere by modifying the vertical distribution of temperature and water vapor, although neither scheme transfers buoyancy consistently. We refer the reader to Tiedtke (1986) for an overview of the parameterization of convection in general circulation models.

3. EXPERIMENTS

3.1. Basic Experiments

The experiments discussed in this paper use either the MCA or Kuo convective parameterization scheme with one of six different *zonally symmetric* SST distributions. These experiments are summarized in Table 1. We will refer to a standard SST distribution (Std) as the observed zonally averaged SST for March 21, symmetrized about the equator, with the SST modified near the poles so temperatures remain above freezing (fig. 2a). The SST distribution denoted by «Peq» has a marked maximum SST peaked on the equator. The SST distribution lebaled «flat» features constant SST equatorward of 30°, with a value equal to the SST on the equator from the standard SST profile. The «Feb1» SST profile is representative of the climatological February temperatures in the central Pacific Ocean where the SST is asymmetric about the equator. The hemispheric asymmetry in the Feb1 SST profile has been emphasized even more in the «Feb2» SST distribution. The case labeled «Oct» uses the climatological October SSTs of the central Pacific and features a slight SST minimum on the equator. The SST distribution for the Std, Peq, Oct and Feb2 are shown in figure 2a. Each experiment is run for at least 80 days, with the standard experiments run for at least 120 days; only data from the last 60 days are used in the time averages. Sharp ITCZ(s) form in each experiment, demonstrating that these intense convergence zones are a robust feature of the Earth's circulation. Initial conditions are taken from an arbitrary day of a prior integration in statistical

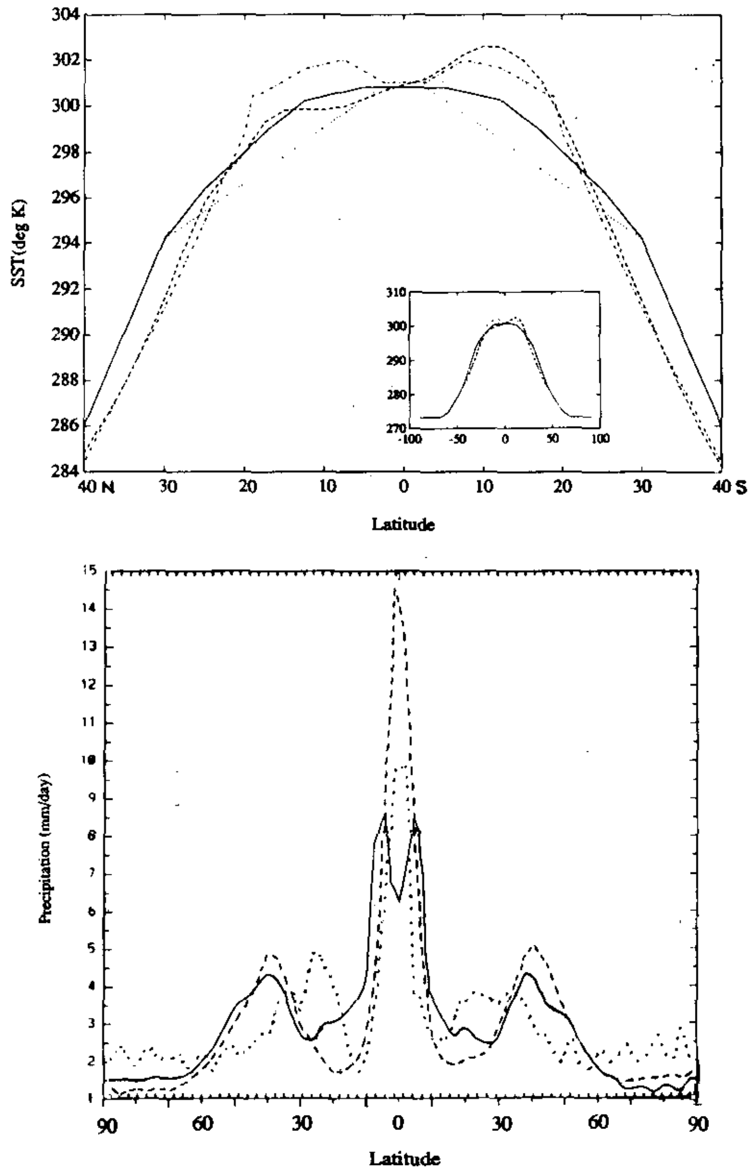

Figure 2.(a)—The prescribed meridional distribution of sea surface temperature vs. latitude for the «standard» experiments discusse in this paper («Std», solid line). The February («Feb2», *dashed line*), October («Oct», *dashed-dotted line*) and peaked («Peq», dotted line) sea surface temperature distributions are also shown. (b) The meridional distribution of zonally averaged precipitation vs. latitude for selected experiments (mm/day); Kuo-Std (solid line), MCA-Std (dashed line) and Kuo-Nwv-Std (dotted line) (see text). In each case the averaged is taken over a 60 day period after a minimum of 20 days spin-up.

steady state. It usually takes less than ten days for the ITCZs to adjust to either a new SST distribution or a new convective parameterization scheme.

The most striking results from the experiments documentd in Table 1 are as follows:

(i) A single general circulation model with identical forcing and boundary conditions yields a tropical circulation that is *qualitatively* changed by changing only the parameterization of convection in the model (Kuo-Std and MCA-Std).

(ii) The model with a Kuo scheme produces two off-equatorial ITCZ with a SST distribution that is peaked on the equator (Kuo-Std) or with SST uniform in the tropics (Kuo-Flat).

The propensity for the Kuo scheme to form two ITCZ is apparent even with the heightened asymmetric February SST boundary conditions (Kuo-Feb2; Table 1 and fig. 2a). The GCM with the Kuo scheme does give a single convergence zone when the SST is sharply peaked (Kuo-Peq) on the equator. We will for the moment concentrate on the differences between Kuo-Std and MCA-Std experiments [1].

Table 1 caption:

The experiments are identified in the left hand column. The case is identified first by the type of convective scheme, either Kuo or moist convective adjustment, and then by the lower boundary sea surface temperature condition (see fig. 2). The second column indicates the location of ITCZ(s) for each model run. The precipitation is found in column three, while the percentage of this precipitation that is convective (not large-scale precipitation) is indicated in column four. The location and speed of the subtropical jets are noted in the last two columns.

Table 1

CASE	*ITCZ LOCATION*		*PRECIPITATION (mm/day)*		*% CONVECTIVE PRECIPITATION*		*JET LOCATION*		*JET SPEED (m/s)*	
	S.H.	N.H.	S.H.	N.H.	S.H.	N.H.	S.H.	N.H.	S.H.	N.H.
Kuo-Flat	7°	7°	7.3	7.0	76%	76%	52°	49°	21	25
Kuo-Feb1	10°	7°	10.8	8.0	71%	77%	40°	46°	46	45
Kuo-Feb2	13°	4°	12.5	8.0	68%	72%	40°	40°	49	45
Kuo-Oct	7°	7°	10.7	10.2	76%	76%	40°	37°	50	48
MCA-Oct	7°	7°	7.4	8.0	62%	62%	40°	36°	51	51
Kuo-Std	4-7°	4-7°	8.3	8.7	80%	80%	40°	40°	39	37
MCA-Std	Eq.		14.6		65%		32°	29°	42°	41°
Kuo-Peq	Eq.		19.0		66%		33°	30°	40°	38°
Kuo-Ste-Nwv	Eq.		10.0		78%		24°	24°	68°	65°

[1] The net precipitation for the Kuo-Std case is due to large-scale precipitation, moist convective precipitation and Kuo precipitation. The MCA scheme in this run, however, accounts for less than 10% of the total precipitation. The MCA scheme is not used in any of the other model integrations that have included the Kuo scheme.

The zonal and time averaged daily rainfall from the model runs with the standard SST distribution and either the MCA or Kuo convective parameterizations is shown in figure 2b. We note that the equatorial ITCZ in the MCA-Std case has significantly more rainfall than the off-equatorial ITCZ in the Kuo-Std case, figure 3, shows the power of 12 hour averaged rainfall versus frequency and latitude for the two cases. As the aqua planet is longitudinally symmetric this figure was produced by combining the statistics at each longitudinal point. The total rainfall is surprisingly white at all latitudes in both cases, with the exception being the Kuo-Std on the equator. The white spectrum is in agreement with ISCCP cloud brightness spectra (Hendon, 1990, personal communication) in the vicinity of the ITCZ. With few exceptions the power in rainfall is larger in the MCA-Std than in the Kuo-Std case at all frequencies and all latitudes, especially equatorward of the rainfall maximum in Kuo-Std. In both cases prominent spectral peaks are associated with the ITCZ, but these peaks are more pronounced in the MCA-Std case. In addition, the intraseasonal oscillation (a.k.a. the Madden-Julian and 30-60 day Oscillation) can be identified in both the Kuo-Std and MCA-Std model, albeit with a period of about 25 days. However, while the phenomenon is difficult to observe in the momentum and precipitation fields in the Kuo-Std case, it is dominant in the MCA-Std case (c.f. the 20-25 day power on the equator in figures 3a and b). The difference in the rainfall spectra between the two cases is remarkable and is simply one facet of the consequences of changing the convective scheme in a GCM.

The zonal velocities are shown for the two cases in figure 4. The jets in the MCA-Std case are faster than in the Kuo-Std run and are situated closer to the equator. The tropospheric zonal velocities are significantly larger in the MCA-Std case between 38°S and 38°N than in the Kuo run except in the lowest model levels equatorward of 20°. We note that the jet axis in the Kuo-Std case is almost vertically oriented, whereas in the MCA-Std case the jet axis has a pronounced equatorward tilt leading to the equatorward position of the jets (in the lower troposphere the location of the axis is almost identical in each of the runs). We will discuss the zonal mean circulations in relation to the position of the ITCZ in Section 4.

The convective heating for the two standard cases is shown in figure 5. Heating and vertical velocity are, to a good approximation, related to each other in the tropics by the static stability (Holton, 1979). Hence, the vertical velocity field resembles the heating distribution in the vicinity of the ITCZs. The heating maximum due to convective processes in the MCA-Std case is found on the equator and is larger than the heating maxima in the Kuo-Std case. We note that the vertical distribution of the time averaged *and* transient convective heating (vertical velocity) are affected by the convective parameterization (c.f., fig. 3 and 5 and the companion paper).

The mass streamfunction (fig. 6) reinforces the differences in the circulation between the Kuo-Std and the MCA-Std cases alluded to above. The meridional circulation in the MCA-Std case is almost 50 % stronger than in the Kuo-Std case, with the upward motion confined to a narrow zone in

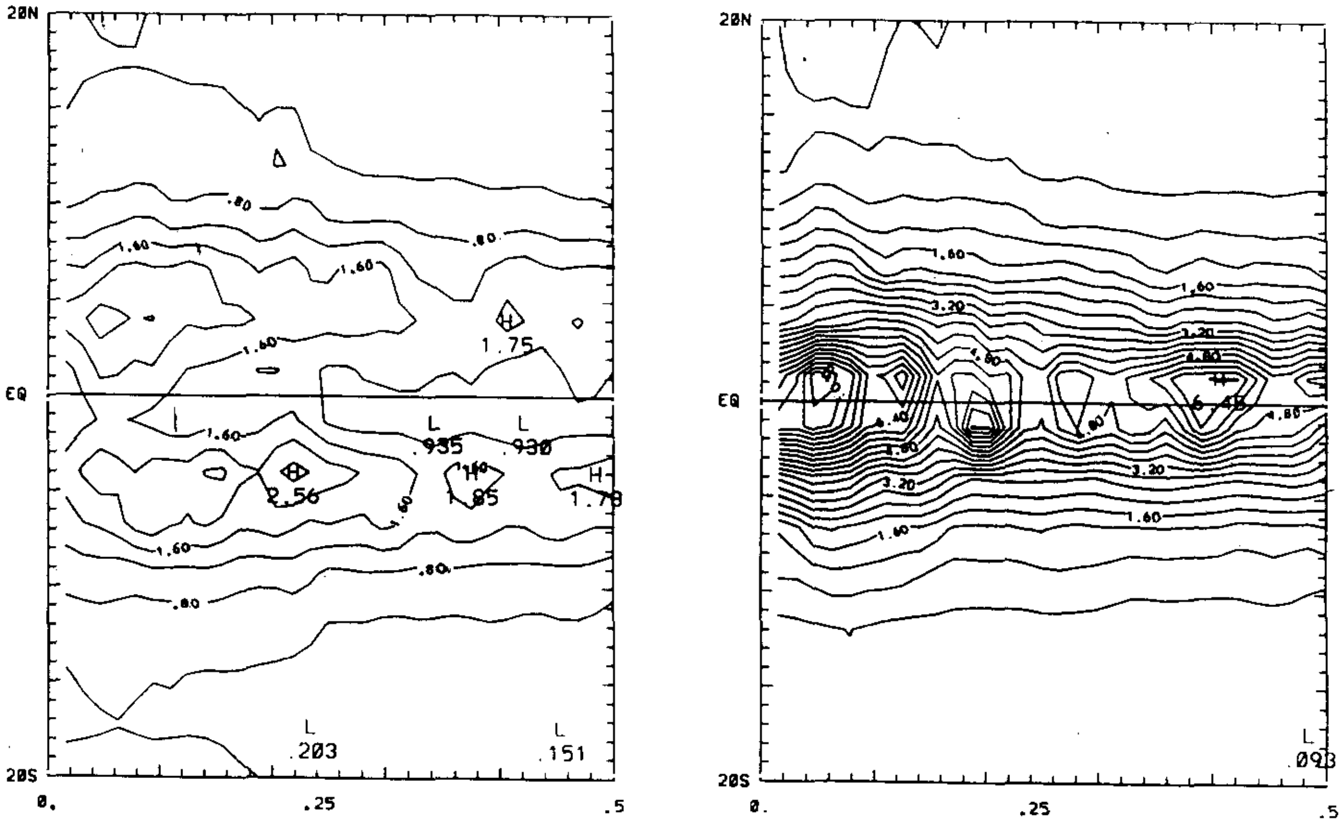

Figure 3.—The power spectrum for twelve hour averaged total precipitation in the (a) Kuo-Std and (b) MCA-Std case is plotted as a function of latitude and frequency. The spectra are based on 60 day time series. Frequency is in cycles per day. Contour interval is 0.4 mm²/day².

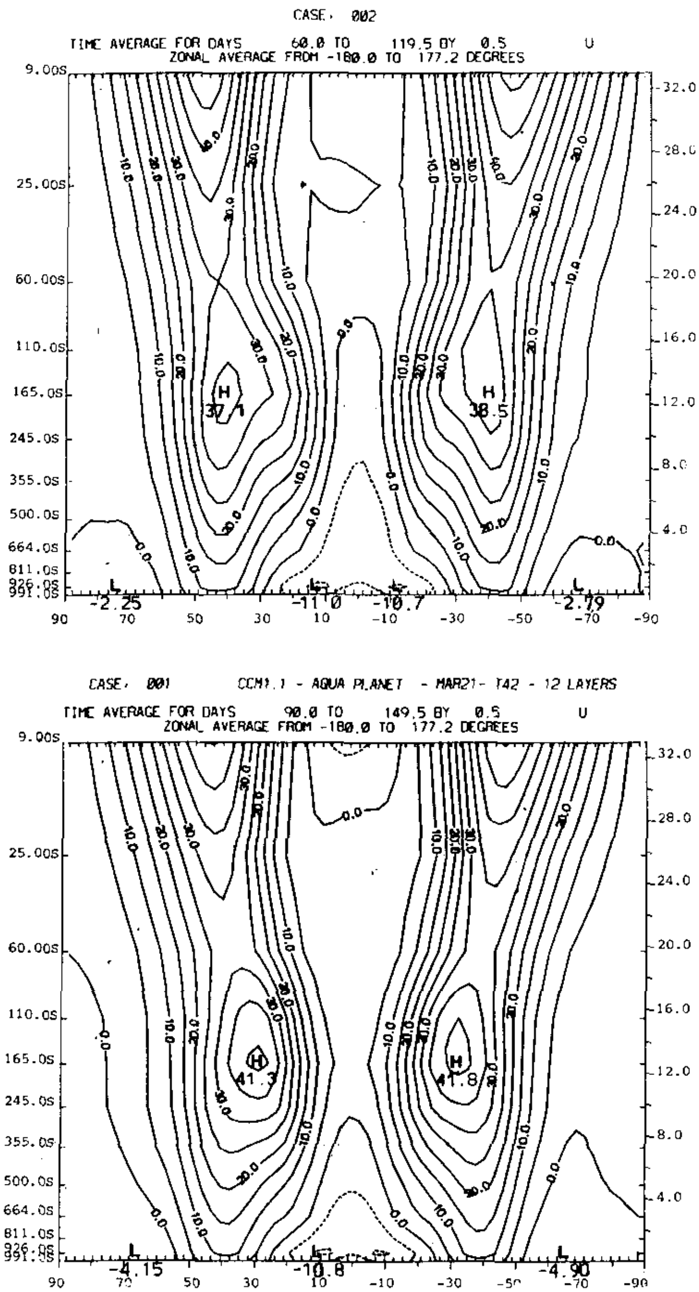

Figure 4.—A meridional cross section of the zonally averaged zonal velocity over the (a) Kuo-Std and (b) MCA-Std case. The time averages are over 60 days. The contour interval is 5 m/s.

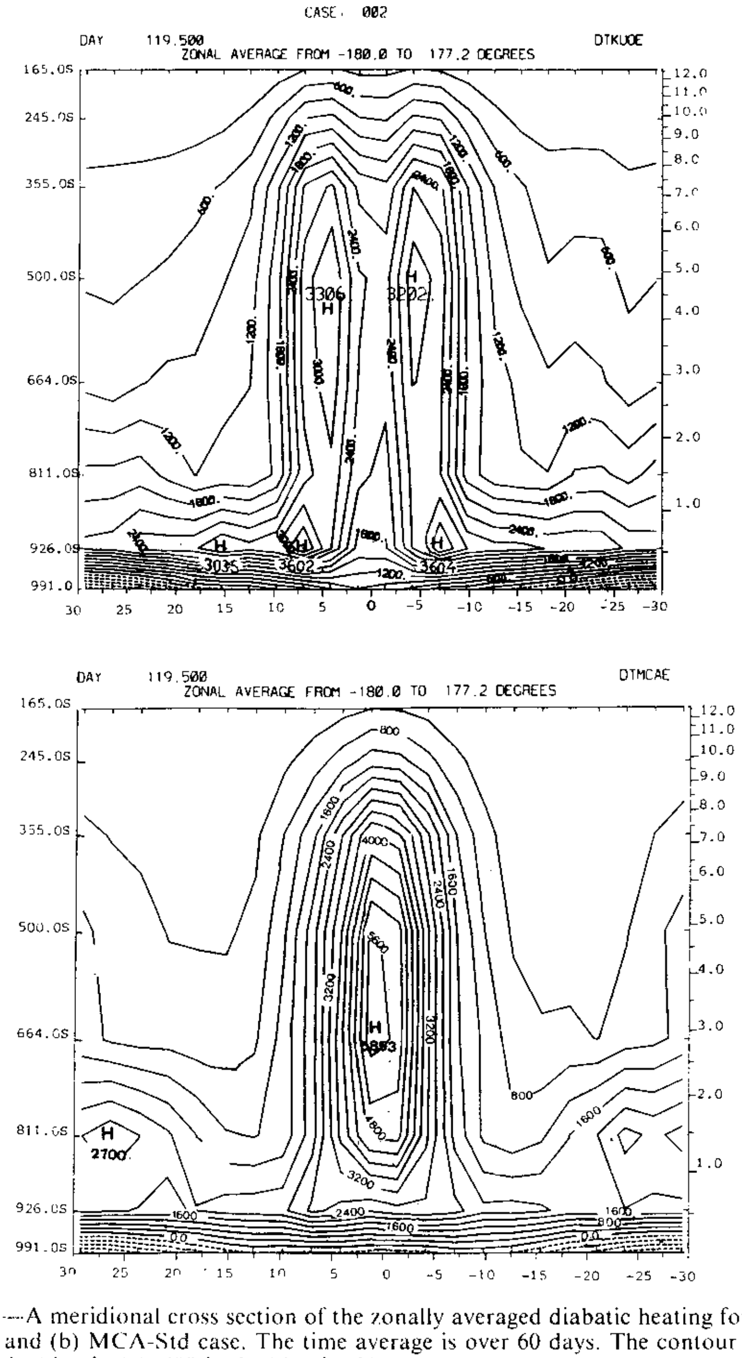

Figure 5.—A meridional cross section of the zonally averaged diabatic heating for the (a) Kuo-Std and (b) MCA-Std case. The time average is over 60 days. The contour interval is 300 joules/day in (a); 400 joules/day in (b).

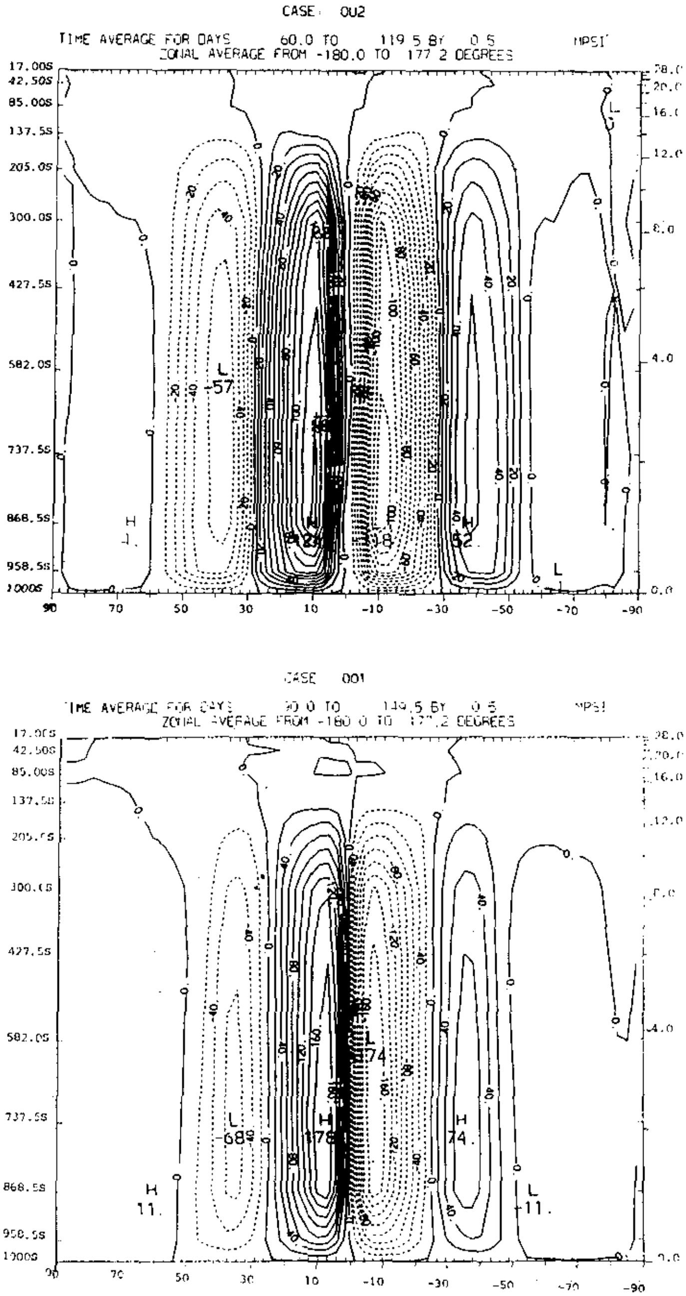

Figure 6.—A meridional cross section of the zonally averaged meridional mass stream function for the (a) Kuo-Std and (b) MCA-Std case. The time average is over 60 day. The contour interval is $1x\ 10^{10}$ kg/m/s in (a); $2x\ 10^{10}$ kg/m/s in (b).

the vicinity of the equator. The rising branch of the Hadley circulation in the Kuo-Std case is latitudinally wider and meridional circulation cells extend further poleward. These results are consistent with Schneider (1977), who argued that a concentrated heat source will produce a Hadley circulation that is stronger than that produced by a diffuse heat source with the same integrated heating.

3.2. A Zonally Symmetric Solution

We have integrated the CCM with the Kuo convective adjustment scheme in a axisymmetric (two dimensional) configuration (Kuo-Std-Nwv) which permist no zonally propagating disturbances. Thus, the only significant model change from the Kuo-Std case is the reduction in the degrees of spatial freedom [2]. After a few days of model integration, the double ITCZ structure in the initial conditions erodes. In the time mean circulation a strong single ITCZ is found on the equator, indicated by the distribution of precipitation displayed in figure 2b. The zonally asymmetric transients are clearly an important element in producing the steady state solution in the Kuo-Std case, moving the ITCZ off the equator and modifying the attendant large-scale mean tropical circulation.

The ITCZ in the axially symmetric CCM (with the Kuo scheme) is found over the warmest water. This is consistent with the results of the other axially symmetric simulations (Schneider, 1977; Schneider and Lindzen, 1977; Pike, 1971; Goswami *et al.*, 1984) and the MCA-Std case, but contrary to the results of the full three dimensional Kuo-Std simulation. The axisymmetric Kuo integration (Kuo-Std-Nwv) *does* allow the physics postulated by Charney (1971) for maintaing off equatorial ITCZs: i.e., the competition between Ekman pumping and the moist static energy. However, the circulation in the Kuo-Std-Nwv case, characterized by one ITCZ on the equator, is contrary to Charney's hypothesis. Holton *et al.* (1971) argue that zonally propagating equatorial waves may help organize convective activity off the equator in the tropics (wave-CISK) through a singularity in the (Ekman) Boundary layer and, hence, may significantly contribute to the zonal time mean convection (the ITCZ). The importance of the zonally asymmetric motions in the Kuo-Std simulation, made apparent by the Kuo-Std-Nwv experiment, is consistent with this hypothesis for maintenance of the off-equatorial ITCZs, but it does not prove that the postulated mechanism is indeed occurring.

Holton *et al.* (1971) specifically suggest 4-5 day waves may be particularly important in organizing surface moisture convergence and, hence, convection off the equator. These waves were implicated, in part, because they are an ubiquitous feature of the tropical troposphere (Wallace and Chang, 1969;

[2] Diffusion is enhanced in Kuo-Std-Nwv case model to stabilize the nomerics in the model "stratosphere".

Reed and Recker, 1971; Nitta *et al.*, 1975; Liebmann and Hendon, 1990). We have analyzed the wave energy at periods near four days for four of the cases in a companion paper and find the convective scheme has a significant impact on both the location of the convection and the equatorial wave-spectrum. For example, the three dimensional structure and the dispersion characteristics of the synoptic energy (frequency and wavenumber, phase and group velocities) in the Kuo-Std case are consistent with a mixed Rossby gravity wave, described by Matsuno (1966); this wave is not found in the MCA-Std case. However, it does not appear that the mixed Rossby gravity waves *alone* account for significant precipitation in Kuo-Std case. Rather, the collapse of the two ITCZ in the Kuo-Std case to one ITCZ in the Kuo-nwv-Std case appears to be due to the reduction of transient mechanisms (i.e., the elimination of zonally propagating Rossby and mixed Rossby Gravity waves) in the two-dimensional geometry that can efficiently organice the boundary layer flow off the equator.

4. THE EFFECT OF THE LOCATION OF THE ITCZ ON THE LARGE SCALE CIRCULATION

In this section we examine the strength and location of the midlatitude jets in relation to the location and strength of the model ITCZs. The position and speed of the jet maximum, and the position and precipitation rate in the ITCZ is given for each of the separate experiments in Table 1. The Kuo-Std-Nwv and Kuo-Flat cases are exceptional. The jets in the Kuo-Flat case are not simply related to the Hadley circulation because extraordinary and discontinuous temperature gradients exist at 30° latitude: this case is not discussed below. The Kuo-Nwv-Std is the only case with no zonally asymmetric waves. Of all the model experiments, the Kuo-Nwv-Std case has the highest jet speeds and the jets are centered closed to the equator (fig. 7); the maximum wind is about 80 % of that expected if a parcel was to conserve angular momentum in traversing from the equator to the latitude of the jet core. The circulation is similar to that given by the non-linear axisymmetric Hadley cell models of Schneider (1977) and Held and Hou (1980) (see, in particular, Held and Hou's numerical results for a non-linear Hadley circulation with moderate vertical diffusion ($5m^2\ sec^{-1}$)). Perhaps the most notable difference between the zonal mean Kuo-Nwv-Std circulation and the calculations presented in Held and Hou (1980) is the pronounced slope of the jet maximum equatorwards from its absolute maximum near 24° and 165 mb. Above 165-110 mb the solution produced by the CCM with westerly winds over the equator is probably dictated by the large horizontal diffusion in the stratosphere. Comparing figures 4 and 7 it is evident that the presence of zonally asymmetric waves decreases the amplitude of the jets and moves them poleward.

The remaining experiments in Table 1 can be categorized into cases in which one ITCZ is found over the equator (MCA-Std, Kuo-Peq), or two

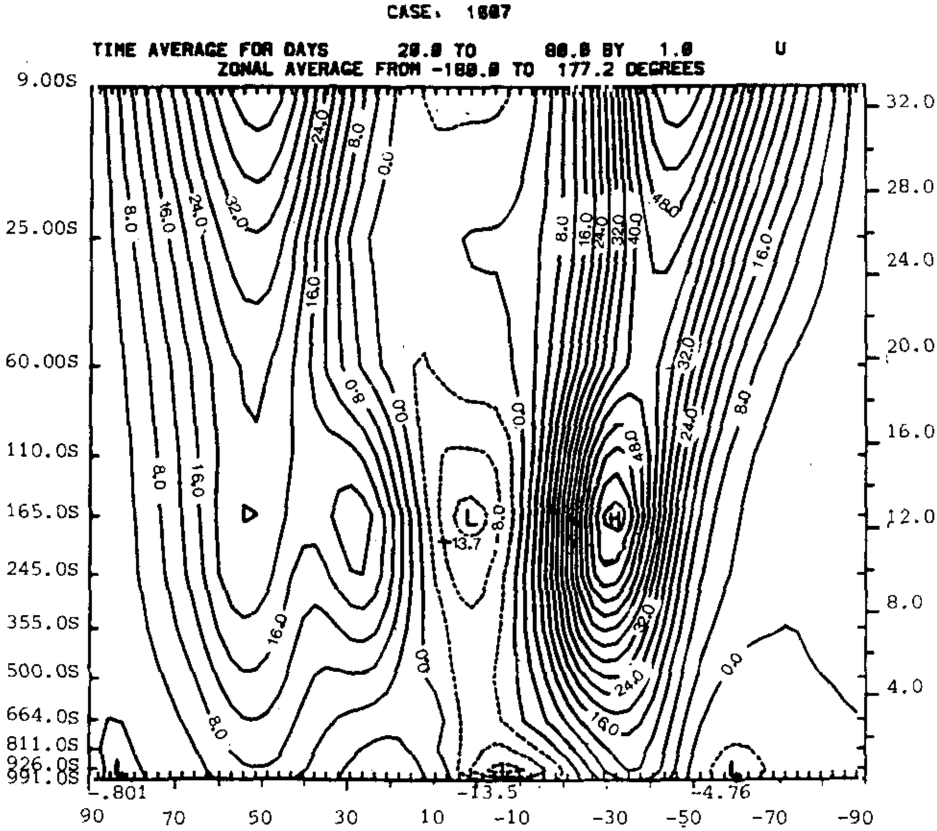

Figure 7.—A meridional croos section of the zonally averaged zonal velocity for the Kuo-Nwv-Std case. The time average is over 60 days. Contour interval is 4 m/s.

ITCZs straddle the ecuator (Kuo-Feb1, Kuo-Feb2, Kuo-Oct, MCA-Oct, Kuo-Std). In doing so, we find that it is the *position* of the ITCZ(s) that determines the location and strength of the mid-latitude jest rather than the amount of precipitation in the ITCZ or the convective scheme that is utilized. Whereas the three cases characterized by a single ITCZ located on the equator feature jet maxima located near 30°, each of the experiments with off-equatorial ITCZs have jets located at about 40° latitude. The jet structure in the single ITCZ cases is much less barotropic than those in the double ITCZ cases: the jet maximum slants down wards and polewards so that in the lower troposphere the maximum winds are located near 40° (e.g., fig. 4b). The jet location is relatively insensitive to how far the ITCZ is situated from the equator, as long as it is off the equator (c.f., Kuo-Feb1, Kuo-Feb2, Kuo-Oct, MCA-Oct, Kuo-Std). Furthermore, in the February cases (Kuo-Feb1, Kuo-Feb2) both the Northern and Southern Hemisphere jets are at the same latitude even though the precipitation is antisymmetric about the equator in both intensity and location.

The speed of the jet maximum is also dependent on the location of the ITCZ(s): the experiments that produce off-equatorial ITCZs generally have stronger jets than those in the experiments that have a single ITCZ. The only notable exception to this is the Kuo-Std case, where the jet speeds are anomalously low in comparison with the other off-equatorial ITCZ cases. The difference in the jet speeds in the single and double ITCZ model cases can be simply understood from angular momentum considerations: an angular momentum conserving parcel will acquire a larger zonal velocity if it travels from 5° to 35° than if it travels from the equator to 30° due to the increased curvature of the earth with latitude.

Finally, the amount of precipitation (which is correlated with the magnitude of the heating and thus the strength of the internal forcing) has little effect on the jet strength or its location (c.f. the Kuo-Peq and MCA-Std and cases, each having a single ITCZ on the equator). The Kuo-Oct and MCA-Oct cases have very similar jet structures and amplitudes, even though the convective scheme and precipitation amount is different in each case. The insensitivity of the jet maxima and location of the jet maxima to the dominant *type* of precipitation is noted and documented in the companion paper.

5. DISCUSSION AND CONCLUSION

We have performed integrations with a general circulation model (NCAR GCM) in an aqua planet configuration, forced with symmetric equinoctal (March 21) insolation in order to examine the dynamics and thermodynamics associated with the Intertropical Convergence Zones (ITCZ). The model spatial truncation is T42. The sea surface temperature (SST) is prescribed and zonally symmetric. Since the ITCZ are intimately tied to the SST and small scale convective processes, we have performed several integrations using various SST distributions. Twin integrations using identical SST and solar insolation but with different parameterization schemes for convection have also been performed.

Qualitative changes in the location of the ITCZ and in the large-scale tropical circulation are realized in the same general circulation model by employing two different parameterizations of deep convection: modified Kuo and Moist Convective Adjustment. The model with the moist convective adjustment parameterization always forms a single ITCZ over the warmest water. By contrast, the Kuo scheme favors a double ITCZ straddling the equator, even given a meridionally flat or 'standard' SST distribution (SST is maximum on the equator, decaying poleward, and zonally symmetric). However, the model with the Kuo scheme does produce one ITCZ over the warmest water (e.g., the Kuo-Peq case) when the warmest water is flanked by very large SST gradients.

We have shown that, with SST maximum on the equator, zonally asymmetric motions are necessary for the model with the Kuo scheme to achieve off-equatorial ITCZ; the two off-equatorial ITCZ converge to one ITCZ on the equator in the absence of the zonally asymmetric motions. These results are contrary to Charney (1966, 1971) who argued that the ITCZ should be off the equator even in the absence of the zonally asymmetric motions. In moving from three dimensions to two dimensions in the model with the Kuo scheme, the collapse of the two off-equatorial ITCZ to one ITCZ on the equator appears to be due to the reduction of transient mechanisms that can efficiently organize the boundary layer flow in the two-dimensional model (i.e., the eliminations of zonally propagating Rossby and mixed Rossby Gravity waves).

We have compared the time mean moist static energy distribution and moist static energy budget for three regions (within the ITCZ, the tropical boundary layer and tropical subsidence regions) in the Kuo-Std and MCA-Std cases in the companion paper. The time mean moist static energy budget is relatively insensitive to the parameterization for deep convection. However, ther are significant differences in the transients that appear in the twin integrations using the two convective parameterizations, including striking differences in the intraseasonal oscillation. The different spatial and temporal scales associated with the heating in the two schemes will favor the forcing of different global wave modes (see, Salby and Garcia, 1987; Garcia and Salby, 1987). An examination of the atmospheric columns immediately before the parameterized convection occurs indicates the mechanisms that maintain the tropical moist static energy budget are different in each of the two cases because of the inherent differences in the adjustment process for deep convection [3].

The sensitivite of the time mean tropical circulation and ITCZ to the specific parameterization for convection is one of the key results of this work. It implies the location of the time averaged convection may be determined through a delicate balance between boundary layer processes, the SST distribution, and the *nature* of the convective adjustment. In the model, the nature of the convection depends on the convective scheme. The tropical circulation in the model with moist convective adjustment scheme is strongly influenced by even weak SST gradients; it takes rather large SST gradients to change the preferred location of convection with the Kuo scheme. It is very likely that strong SST gradients determine the position of the ITCZ by enhancing the boundary layer convergence over the region of maximum SST via hydrostatically induced pressure gradients (Schneider and Lindzen, 1976, Lindzen and Nigam, 1987; Tiedtke *et al.* 1988; Battisti *et al.*, 1992). However, there are regions in the deep tropics where SST gradients are weak enough (e.g., annually in the Indian and western Pacific Ocean, and in boreal spring in the central and far eastern Pacific) that SST may not determine the

[3] The analysis of the transients and the atmospheric columns just prior to convection is reported in the companion paper submitted to the *Journal of Atmospheric Sciences*.

location of the ITCZ (see, fig. 1). The position of the ITCZ in these regions may be determined by processes internal to the atmosphere (specifically the convective and boundary layer processes). Our results specifically indicate that in these regions the qualitative aspects of a general circulation model climatology could be quite sensitive to the parameterization of the subgrid scale convection. Moreover, our results indicate that even when the zonal mean tropical circulation and the location of the ITCZs are intensitive to the convective scheme (i.e., in regions of large SST gradients), the nature of the tropical transients will be highly dependent on the convective scheme.

Various investigators have reported on the global sensitivity of climate and forecast models to the parameterization scheme for convection (e.g., Donner *et al.,* 1982; Donner, 1986; Tiedtke, 1984; Tiedtke *et al.* 1988). These impacts are, in general, subtle outside of the tropics. However , the impact of different subgrid scale cumulus parameterizations on the climate of a coupled atmosphere/ocean model may not be as subtle. Our results indicate that the mean and transient atmospheric circulation west of the dateline in the tropics may be very sensitive to the quantitative and subtle aspects of convection. Indeed, Tiedtke *et al.* (1988) noted that employing a Kuo convective parameterization in the ECMWF model resulted in a major change in the tropical 850 mb circulation. If a comparable change is registered in the surface wind, then the climatological wind stress and hence the SST will be affected. The variability in the climate of the tropical Pacific is presently dominated by the interannual ENSO phenomenon (Rasmusson and Carpenter, 1982) — a phenomenon that has world-wide impacts (e.g., see Rasmusson and Wallace (1983) and references therein for an overview of the global ENSO phenomenon). The chararcteristics and strength of ENSO, however, are thought to be extremely sensitive to the climatological mean atmosphere/ocean state (e.g., Battisti and Hirst, 1989). Thus, an assessment of the validity of the climate simulated from a model of the coupled atmosphere/ocean system will likely require, in part, the evaluation of both the steady and the transient circulation associated with the convective adjustment processes in the atmosphere and the atmospheric general circulation model.

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REFERENCES

Anthes, R. A. (1977): A cumulus parameterization scheme utilizing a one-dimensional cloud model. *Mon. Wea. Rev.* **105**, 270-286.

Battisti, D. S. and A. C. Hirst (1989): Interannual variability in a tropical atmosphere-ocean model: Influence of the basic state, ocean geometry and nonlinearity. *J. Atmos. Sci.* **46**, 1687-1712.

Battisti, D. S., A. C. Hirst, E. S. Sarachik and P. Tian (1991): A Consistent Model for the Steady Atmospheric Surface Circulation in the Tropics. In preparation.

Chang, C. P. (1973): A dynamical model of the Intertropical Convergence Zone. *J. Atmos. Sci.* **30**, 190-212.

Charney, J. G. (1966): Some remaining problems in numerical weather prediction. Advances in numerical weather prediction. The Travelers Research Center, Inc., Hartford, CT., p. 61-70.

Charney, J. G. (1971): Tropical cyclogenesis and the formation of the Intertropical Convergence zone. Mathematical problems in geophisical sciences. Lecture in Applied Mathematics, 13, W.H. *Reid, ed. American Mathematics Soc.* 355-369.

Charney, J. G. (1973): «Reply». *J. Atmos. Sci.* **31**, 834-835.

Deardorff, J. W. (1972): Parameterization of the planetary boundary layer for use in a general circulation model. *Mon. Wea. Rev.* **100**, 93-106.

Donner, L. J., H. L. Kuo and E. J. Pitcher (1982): The significance of thermodynamic forcing by cumulus convection in a general circulation model. *J. Atmos. Sci.* **39**, 2159-2181.

Donner, L. J. (1986): Sensitivity of the thermal balance in a general circulation model to a parameterization for cumulus convection with radiatively interactive clouds. *J. Atmos. Sci.* **43**, 2277-2288.

Dorman, C. E. and R. H. Bourke (1979): Precipitation over the Pacific Ocean, 30°S to 60°N. *Mon. Wea. Rev.* **107**, 896-910.

Dunkerton, T. (1989): Nonlinear Hadley circulation driven by asymmetric differential heating. *J. Atmos. Sci.* **46**, 956-974.

Garcia, R. R. and M. L. Salby (1987): Transient response to localized episodic heating in the tropics. Part II: Far-field behavior. *J. Atmos Sci.* **44**, 499-530.

Goswami, B. N., J. Shukla, E. K. Schneider and Y. C. Sud (1984): Study of the dynamics of the intertropical Convergence Zone with a symmetric version of the GLAS climate model. *J. Atmos. Sci.* **41**, 5-19.

Hayashi, Y.-Y. and A. Sumi (1986): The 30-40 day oscillation simulated in an «Aqua Planet» model. *J. Meteor. Soc. Japan* **64**, 415-465.

Held, I. M. and A. Y. Hou (1980): Nonlinear axially symmetric circulations in a nearly inviscid atmosphere. *J. Atmos. Sci.* **37**, 515-533.

Holton, J. R. (1979): An Introduction to Dynamic Meteorology. *Academic Press, New York.* pp. 301.

Holton, J. R., J. M. Wallace and J. A. Young (1971): On boundary layer dynamics and the ITCZ. *J. Atmos. Sci.* **28**, 275-280.

Jaeger, L. (1976): Monatskarten des Niederschlags für die ganze Erde. Betichte des Deutschen Wetterdienstes, 18, No. 139, 38 pp.

Kiehl, J. T., R. J. Wolski, B. P. Briegleb and V. Ramanathan (1987): Documentation of Radiation and Cloud Routines in the NCAR Community Climate Model (CCM1). NCAR Tech. Note, NCAR/TN-288+IA, National Center or Atmospheric Research, Boulder.

Krishnamurti, T. N., S. Low-Nam and R. Pasch (1983): Cumulus parameterization and rainfall rates II. *Mon Wea. Rev.* **111**, 815-828.

Kuo, H. L. (1965): On formation and intensification of tropical cyclones through latent heat release by cumulus convection. *J. Atmos. Sci.* **22**, 40-63.

Kuo, H. L. (1974): Further studies of the parameterization of the influence of cumulus convection of large-scale flow. *J. Atmos. Sci.* **31**, 1232-40.

Lau, N.-C., I. M. Held and J. D. Neelin (1988): The Madden-Julian Oscillation in an idealized General Circulation Model. *J. Atmos. Sci.* **45**, 3810-3832.

Liebmann, B. L. and H. H. Hendon (1990): Synoptic-scale disturbances near the equator. *J. Atmos. Sci.* **47**, 1463-1479.

Lindzen, R. S. and S. Nigam (1987): On the role of sea surface temperature gradients in forcing low level winds and convergence in the tropics. *J. Atmos. Sci.* **44**, 2440-2458.

Lindzen, R. S. and A. Y. Hou (1988): Hadley circulations for zonally averaged heating centered off the equator. *J. Atmos. Sci.* **45**, 2416-2427.

Manabe, S. J. Smagorinsky and R. F. Strickler (1965): Simulated climatology of a general circulation model with a hydrologic cycle. *Mon. Wea. Rev.* **93**, 769-799.

Matsuno, T. (1966): Quasi-geostrophic motions in the equatorial area. *J. Meteor. Soc. Japan* **44**, 25-42.

Neelin, J. D. and I. M. Held (1987): Modeling tropical convergence based on the moist static energy budget. *Mon. Wea. Rev.* **115**, 3-12.

Nitta, T., Y., Nakagomi, Y. Suzuki, N. Hasegawa, and A. Kadokura (1985): Global analysis of the lower tropospheric disturbances in the tropics during the northern summer of the FGGE year. Part I: Global Features of the disturbances. *J. Meteor. Soc. Japan* **63**, 1-19.

Pike, A. C. (1971): Intertropical Convergence Zone Studied with an interacting atmosphere and ocean model. *Mon. Wea. Rev.* **99**, 469-477.

Rasmusson, E. M. and T. H. Carpenter (1982): Variations in tropical sea surface temperatures and surface wind fields associated with the Southern Oscillation and El Niño. *Mon. Wea. Rev.* **110**, 354-384.

Rasmusson, E. M. and J. M. Wallace (1983): Meteorological aspects of the El Niño/Southern Oscillation. *Science* **222**, 1195-1202.

Reed, R.J. and E. E. Recker (1971): Structure and properties of synoptic-scale wave disturbances in the equatorial western Pacific. *J. Atmos. Sci.* **28**, 1117-1133.

Saha, K. (1971): Mean cloud distributions over tropical oceans. *Tellus* **23**, 183-195.

Salby, M. L. and R. R. Garcia (1987): Transient response to localized episodic heating in the tropics. Part I: Excitation and short-time near-field behavior. *J. Atmos. Sci.* **44**, 458-498.

Schneider, E. K. (1977): Axially symmetric steady-state models of the basic state for instability and climate studies. Part II.Nonlinear calculations. *J. Atmos. Sci.* **34**, 280-296.

Schneider, E. K. (1984): Response of the annual and zonal mean winds and temperatures to variations in the heat and momentum sources. *J. Atmos. Sci.* **41**, 1093-1115.

Schneider, E. K. and R. S. Lindzen (1977): Axially symmetric steady state models of the basic state for instability and climate studies. Part I. Linear calculations. *J. Atmos. Sci.* **34.**, 263-279.

Swinbank, R., T. N. Palmer and M. K. Davey (1988): Numerical simulations of the Madden and Julian Oscillation. *J. Atmos. Sci.* **45**, 774-788.

Taylor, R. C. (1973): An atlas of Pacific Islands rainfall. Rep. HIG-73-9, Hawaii Institute of Geophysic, 7 pp.

Tiedtke, M. (1984): The effect of penetrative cumulus convection on the large-scale flow in a general circulation model. *Beitr. Phys. Atmosph.* **5**, 216-239.

Tiedtke, M. (1986): Parameterization of cumulus convection in large-scale models. In «Physically based modelling and simulation of climate and climate change». Vol. 1. Ed. M. E. Schlesinger, Kluwer Academic, 375-431.

Tiedtke, M., W. A. Heckley and J. Slingo (1988): Tropical forecasting at ECMWF: The influence of physical parameterization on the mean structure of forecast and analyses. *Q. J. Royal Meteor. Soc.* **114**, 639-664.

Wallace, J. M. and C. P. Chang (1969): Spectrum analysis of large-scale wave disturbances in the tropical lower troposphere. *J. Atmos. Sci.* **26**, 1010-1025.

Williamson, D. L., J. T. Kiehl, V. Ramanathan, R. E. Dickinson and J. J. Hack (1987): Description of NCAR Community Climate Model (CCM1). NCAR Tech. Note, NCAR/TN-285+STR, National Center or Atmospheric Research, Boulder, CO NTIS PB87-203782/AS, 112 pp.