THE ORIGINS OF ITCZS, MONSOONS AND MONSOON ONSET—A REVIEW

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ABSTRACT Intertropical convergence zones (ITCZs), monsoons and monsoon onset are among the most prominent of atmospheric phenomena. Understanding their origins is fundamental to a full understanding of the atmospheric general circulation and has challenged meteorologists for a very long time. There has been important progress in understanding these phenomena in recent years, and in this article, recent developments are reviewed. First, contrary to conventional belief, land-sea thermal contrast is not necessary for monsoons to form. Second, monsoon onset occurs when there is a sudden poleward jump of an ITCZ during its annual cycle of latitudinal movement. A monsoon, then, is an ITCZ after its poleward jump. Third, the SST latitudinal maximum is not the most significant, or even a necessary, factor in the formation of an ITCZ; there are other important, if not more important, factors. These factors are the interaction between convection and surface fluxes, the interaction between convection and radiation, and the earth's rotation. Finally, the recent understanding of how ITCZs form has led to a conceptual explanation for the origin of the double ITCZ bias in GCM simulations.

Keywords: Monsoon, Monsoon Onset, ITCZ

1 INTRODUCTON

Intertropical convergence zones (ITCZs) are a component of the Hadley/Walker circulation. These are regions where surface air converges and rises into the upward branch of the Hadley/Walker circulation. The latent heat released in ITCZs drives (or, more precisely, interacts with) the Hadley/Walker circulation. The associated clouds are easily seen in satellite pictures either as instantaneous images (Figure 1) or as time averages (e.g., Figure 12.4 of Holton 2004). At any given instant, an ITCZ is a string of tropical synoptic waves, and each wave is associated with a cluster of clouds. These cloud clusters oscillate, with a period of about two weeks, between a more connected state (such as in Figure 1) and a broken-up state (Figure 1 of Ferreira and Schubert 1997, Wang and Magnusdottir 2005). The broken-up state can lead to tropical cyclogenesis. In a time (e.g., monthly)-mean sense, ITCZs appear as continuous cloud bands of varying latitudinal extent in the longitudinal direction, presumably due to zonal variation in surface conditions such as sea surface temperature (SST), land distribution, and land characteristics. Figure 2a shows the monthly-mean precipitation in the tropics for the hemisphere east of 30°E averaged from 1979 to 1998. Figure 2b shows the same for the rest of the tropics. Figs. 2a and 2b show more concentrated precipitation regions, i.e., ITCZs, over the oceans and over land that is surrounded by oceans of low SST, such as Central and South America.

For the purpose of this review article, ITCZs are equated with regions of high precipitation in the tropics in a time (e.g., monthly-averaged sense. Thus, in Figure 2, all regions between 23.5° N&S with a rainfall amount greater than 5 mm/day can be considered ITCZs. Thus, ITCZs include not only the convergence zone between the trade winds, such as in the eastern Pacific, but also the convergence zones in the western Pacific and in the Indian Ocean. This is consistent with the basic definition of an ITCZ being the surface component of the ascending branch of the Hadley/Walker circulation. In addition, we consider the convergence zone northeast of Australia--often called the south Pacific convergence zone (SPCZ)--to also be an ITCZ.

ITCZs are where tropical cyclones form and travel before veering into higher latitudes. This is clear from a comparison of time-averaged ITCZ cloud pictures and plots of tracks of tropical cyclones accumulated over a number of years (Figure 1 of Emanuel 2003), since there is considerable amount of overlap between the two.

The importance of studying ITCZs lies not only in satisfying our scientific curiosity but also in improving various forecasts. The locations and intensities of ITCZs affect surface wind distribution in the tropics, which is a crucial factor in the air-sea interaction that is at the core of El Nino. The pressing need to improve the forecast and simulation of El Nino invariably points to the necessity of a good simulation of ITCZs. This in turn points to the importance of a thorough theoretical understanding of ITCZs.

Forecasting El Nino is but one type of forecast that relies on a good simulation of ITCZs. More generally, climate forecasts, such as drought and flood forecasts, depend on a forecast model's ability to correctly simulate the largest feature of the atmospheric general circulation: the Hadley/Walker circulation. The Hadley/Walker circulation is intimately tied to the trade and monsoonal winds, and depends, for its energy source, on the latent heat released in ITCZs. Many atmospheric general circulation models (GCMs) have the so-called "double ITCZ bias" problem: i.e., a strong double ITCZ occurs where observations show only a weak or a single ITCZ (e.g., Bacmeister et al. 2007). The empirical solutions offered thus far for this problem have not been very successful, and carry with them considerable side-effects. Thus, the need to know more about ITCZs is obvious. Moreover, a better simulation of ITCZs also means a better simulation of the Madden-Julian oscillation (MJO). The MJO is a 40-to-60 day oscillation of the convection within the ITCZs in the Indian Ocean and western Pacific that has global impact. Many GCMs are poor at simulating the seasonal variation in MJO intensity (Slingo et al. 1996), which is strongest in boreal winter. This is a result of the GCMs' failure to simulate the seasonal variation--including the latitudinal movement--of ITCZs correctly. Naturally, one would expect that a better understanding of the origin, including the location and intensity, of ITCZs would eventually lead to better GCM simulations of the MJO. Furthermore, ITCZs are the breeding grounds for tropical cyclones, and understanding and forecasting tropical cyclogenesis require an understanding and a good simulation of ITCZs. Finally, the study of ITCZs is closely related to the study of monsoons, whose forecasts are of greatest importance to those affected by them.

In the study of ITCZs, some obvious questions arise: why should ITCZs exist and what determines their locations and intensities? Since ITCZs are a component of the Hadley/Walker circulation, these questions could be enlarged to include why the Hadley/Walker circulation exists and what determines its structure and intensity. We will not undertake these larger questions, however, which involve the latitudinal extent of the Hadley/Walker circulation and the interaction between it and middle latitude disturbances, but will limit our scope to ITCZs themselves.

Monsoons are important components of the atmospheric general circulation. The cause of monsoons was first attributed to land-sea thermal contrast on a continental scale by Halley (of Halley's Comet fame) in 1678. Halley's explanation has become the textbook explanation, but a recent study has challenged this explanation Chao and Chen (2001). This challenge is supported by experiments using an atmospheric general circulation model and will be reviewed here. We will also review the argument of Chao and Chen (2001) that a monsoon is no more than an ITCZ and its associated wind circulation, sufficiently displaced (e.g., more than 10°) from the equator during its annual cycle of latitudinal movement. This annual cycle of latitudinal movement of ITCZs is not always gradual. Somewhere during the cycle, there is a sudden poleward jump, which can be interpreted as the monsoon onset. In other words, a monsoon is an ITCZ after its poleward jump—i.e., after the monsoon onset. Thus, the origins of ITCZs, monsoons and monsoon onset should be studied together, and they are the topics of this review.

We will briefly review the previous theories of ITCZ latitudinal location first, and then review our own recently proposed theory. Next, we will present a comparison between our theory and previous theories. Our own ITCZ theory is still not comprehensive; thus, a discussion of future research directions will follow at the end of our review of the ITCZ theories. We will then review recent studies on the origins of monsoons and their onset, and how these origins are linked to one another.

2 PREVIOUS ITCZ THEORIES

ITCZs have stood as a puzzle to be unraveled, and there has been no shortage of contending theories attempting to explain them. The most dominant early theory of ITCZ latitudinal location is that of Charney (1971). Charney's ITCZ theory is based on the theory of conditional instability of the second kind (CISK), which he (and Ooyama 1964 at around the same time) proposed to explain tropical cyclogenesis. In CISK theory, convective heating results from boundary-layer frictional moisture convergence (we will see that this is a fundamental misstep). Thus, according to CISK theory, Ekman boundary-layer convergence (also called Ekman pumping) brings in moisture to fuel the growth of a tropical disturbance, and the growth of this disturbance in turn amplifies the strength of the boundary-layer convergence. This positive feedback is, according to the CISK theory, at the core of tropical cyclogenesis. Charney derived a zonally-symmetric version of CISK theory and used it to explain the ITCZ. In Charney's interpretation, the CISK mechanism is favored by a large Coriolis parameter. Thus, ITCZs have a tendency to form at the poles. However, the moisture content in the equatorial region is much higher than in higher latitudes. As a result of the compromise between these two factors, the ITCZ is located close to but away from the equator.

Charney's ITCZ theory was quite influential. Many tried to embellish upon his idea. Holton et al. (1971) proposed an ITCZ theory also based on the efficiency of Ekman pumping. Instead of zonal symmetry, he allowed zonal variation, and proposed that the Doppler-shifted frequency of tropical synoptic waves is equal to the Coriolis parameter, and that this should determine the latitude of the ITCZ. Lindzen (1974) pointed out that according to Holton's theory, the diurnal variation of convection should be a maximum at 30°N and S, but this is not what is observed. Lindzen proposed his own theory based on the wave-CISK idea, in which the CISK idea was modified so that boundary-layer frictional convergence was replaced by convergence provided by waves. Hess et al. (1993) and Waliser and Somerville (1994) also utilized Charney's idea in their studies.

Charney's ITCZ theory turned out to be in conflict with experimental results. Sumi (1992) conducted an experiment using a general circulation model (GCM) in which he replaced all landmass with ocean and specified a uniform sea-surface temperature (SST). The model radiation package was replaced by a scheme that restored the globally horizontally-averaged temperature to a prescribed vertical profile, with the amount of restoration being applied uniformly at each model level. In his experiments, he obtained either a single ITCZ over the equator or a double ITCZ straddling the equator, depending on the model's horizontal resolution. This result clearly did not support the Charney ITCZ theory, which, with its second factor removed (by the globally-uniform SST and radiative cooling), would yield ITCZs at the poles.

Sumi's model experiments were not used immediately to refute Charney's theory. It took a while before the implications of his experiments were understood Chao and Chen (2004). However, Sumi's experiments were not the first that contradicted Charney's theory. In fact, as early as 1971, Pike's (1971) experiments with a zonally-symmetric atmospheric model with uniform SST already had shown that the simulated ITCZ existed in the tropics, not at the poles. Like Sumi's experiments, the significance of Pike's experiments has only been recognized recently. The theoretical reason why

Charney's ITCZ theory failed will be discussed in subsection 3.2, after recent developments in the ITCZ theory under uniform SST are reviewed.

3 RECENT DEVELOPMENTS IN ITCZ THEORY

Earlier ITCZ theories were developed based on simplified analytic models. In contrast, more recent developments in ITCZ theory are based on the interplay between theory and GCM model experiments.

3.1 Aqua-planet model studies of the ITCZ with globally- and temporally-uniform SST and solar angle

3.1.1 Aqua-planet model experiments

The vast oceanic areas that are covered by ITCZs hint that the basics of ITCZs can be more easily understood in an aqua-planet setting. An aqua-planet (AP) model results from replacing all landmass in a GCM with ocean. If only the atmosphere is being studied, there is no need to specify the ocean depth; only the SST will be specified. If, however, ocean- atmosphere interaction is involved, the ocean depth is specified to be a global constant, and the SST is free to vary. An aqua-planet model with a prescribed SST avoids the complications of landmass and ocean-atmosphere interactions and thus simplifies the problem. This is not to say that landmass or ocean-atmosphere interactions are not important; but one should start with more basic settings and determine if they are sufficient. In fact, since ITCZs exist mostly over oceans, an aqua-planet model with prescribed SST should contain the mechanisms that are responsible for ITCZs. Once the ITCZ under aqua-planet settings with a prescribed SST is understood, one can then go on to consider the modifying effects of landmass and ocean-atmosphere interactions.

As mentioned in the preceding section, Sumi (1992) made some important discoveries in his experiments with an aqua-planet model with a prescribed globally-uniform SST. In these experiments, in lieu of a radiation package, he simply restored the vertical profile of the globally-averaged temperature to a fixed vertical profile, and applied the restored amount uniformly throughout the globe. He used the cumulus scheme of Kuo (1965). Sumi found that global general circulation could still exist under this type of setting--without the pole-to-equator gradient of radiative-convective equilibrium temperature that was previously considered the basic cause of general circulation. Although this general circulation is far from what is observed, it does have a Hadley circulation and an ITCZ. Sumi also found that the ITCZ is at the equator when the model horizontal resolution is low, and moves away from the equator (to around 14° N&S--i.e., a double ITCZ) when the horizontal resolution is doubled. We will see later that the double ITCZ in Sumi's experiment is not the result of a higher model horizontal resolution per se.

Other researchers have also done experiments with an aqua-planet model based on different GCMs. Kirtman and Schneider (2000), using an AP GCM with globally-uniform SST based on the Center for Ocean-Land-Atmosphere Studies (COLA) GCM--which used the relaxed Arakawa-Schubert cumulus parameterization scheme (RAS, Moorthi and Suarez 1992)--obtained a single ITCZ over the equator. Chao (2000), who used an AP model with globally-uniform SST and solar angle based on the Goddard Earth Observing System version 2 GCM, found that when the cumulus parameterization scheme was switched from Manabe's moist convective adjustment (MCA) scheme Manabe et al. (1965) to RAS, the ITCZ switched from a single ITCZ over the equator to a double ITCZ straddling the equator. This double ITCZ can be unstable, and often only one component of it shows up away from the equator; but this is quite distinct from an ITCZ over the equator obtained with MCA. Chao and Chen (2001) further found that by requiring the boundary-layer relative humidity to exceed a certain threshold in order for RAS to operate, and by raising this threshold, the simulated ITCZ could be switched from a double ITCZ to a single ITCZ over the equator. Hess et al. (1993) also found the ITCZ to be sensitive to the cumulus parameterization scheme when using an aqua-planet model with SST varying in the latitudinal direction.

3.1.2 Explanation of the aqua-planet model results

Obviously, it is necessary to understand the above ITCZ results in an AP GCM with globally-uniform SST and solar angle before it is possible to understand the ITCZ under realistic conditions. Chao and Chen (2004) offered the following explanation for the above ITCZ results. Under globally-uniform SST and solar angle, the settings for one horizontal location are the same as for another, except for the Coriolis parameter. If the Coriolis parameter is set at a constant value or at zero for all model grids, then the time-mean precipitation should either be globally-uniform or have a Benard-cell-like structure.

As shown by Sumi's experiments, when the Coriolis parameter is assigned its real value, convection has a preferred latitude, and this preferred latitude depends on the model design, particularly on the cumulus parameterization scheme. Therefore, a logical step is to look into the effects of the Coriolis parameter (i.e., the earth's rotation rate projected onto the local vertical axis) on convection and the role played by the cumulus parameterization scheme in these effects. We have done such an investigation Chao and Chen (2001, 2004) and it is described in the following two paragraphs.

The Coriolis parameter has two effects on convection. The first effect is due to its equivalence to vertical stratification (i.e., vertical stability, as expressed by the vertical gradient of potential temperature for dry convection). The combination of the divergence equation $\partial\delta/\partial t = f\,\zeta + \ldots$ and the vorticity equation $\partial\zeta/\partial t = -f\,\delta + \ldots$ under an f-plane setting gives: $\partial^2\delta/\partial t^2 = -f^2\,\delta + \ldots$, where δ is divergence, ζ vorticity, and f the Coriolis parameter. The other terms not shown on the right-hand sides of these equations do not contain f. This equation, excluding the other terms on the right-hand side represented by the dots, has the same form as the equation that governs a simple spring, i.e., $\partial^2 x/\partial t^2 = -kx$. Like a spring, which resists both compression and stretching, the Coriolis force resists both convergence and divergence. A convective system is characterized by low-level convergence and upper-level divergence. Resistance to both is equivalent to resistance to upward vertical motion at the center and to downward vertical motion in the surrounding areas--which is what vertical stratification does. This is why rotation has an effect on convection equivalent to vertical stratification. Thus, if this first effect of the Coriolis parameter is operating alone, the equator is the favored location for convection. In other words, the equator acts as an attractor for the ITCZ, which consists of a string of synoptic-scale convective systems. An ITCZ that is located away from the equator thus experiences an attraction toward the equator due to this attractor.

The second effect of the Coriolis parameter on convection is due to its influence on boundary-layer winds. In the presence of the Coriolis force, the boundary-layer air converging towards the center of a synoptic-scale convective system takes on a spiral path. The convergence in the boundary layer creates vorticity, and therefore, for the same intensity of synoptic-scale convection (or for the same amount of boundary-layer convergence--i.e., for the same amount of surface radial winds) the surface wind speed is higher when the Coriolis parameter is present than when it is absent, because of the tangential wind component generated by the Coriolis force. A higher surface wind speed means more surface evaporation and thus more energy available for convection. Therefore, this second effect of the Coriolis parameter on convective systems makes the poles--where the Coriolis parameter is greatest--the most preferred locations for convection to occur. In other words, the poles also act as attractors for the ITCZ.

It is easy to see that in an axisymmetric model, both effects of the Coriolis parameter still operate. In the explanation for the second effect of the Coriolis parameter, the roles of radial and tangential winds are replaced by those of meridional and zonal winds, respectively.

The balance of the two opposing effects of the Coriolis parameter on the synoptic-scale convective systems that comprise the ITCZ determines the latitudinal location of the ITCZ under uniform-SST and uniform-solar angle conditions. If one effect overwhelms the other, the ITCZ occurs either at the equator or at the poles. The experimental results, however, show the ITCZ residing either at the equator or at ~15° away from the equator. Thus, the assumption that one effect overwhelms the other is not always valid, and it is necessary to look at these two effects more closely to understand how the balance between the two is achieved. This balance must be related to the cumulus parameterization scheme, since the experimental results depend on it. However, we should point out that the cumulus parameterization scheme--though important--is not the only model physics component that matters. Radiation and boundary-layer processes sustain the vertical instability that allows convection to take place. Therefore, parameterizations of these processes play roles in model-simulated ITCZs as well.

To delve deeper into the balance between the two effects of the Coriolis parameter, one need look at the cause of convection, which is vertical instability in the presence of the Coriolis parameter. When the squared frequency of the inertial gravity wave,

$$\omega^2 = f^2 + \alpha^2 N^2 + |F|, \qquad (1)$$

turns negative, convection occurs Eq. 8.4.23 of Gill (1982). Here, N^2 is the vertical stability, $|F|$, the stabilization due to friction, and α, the ratio of the vertical scale to the horizontal scale of the wave or the convective cell. When α is large, as in the case of individual clouds of small horizontal scale, f can be ignored. However, for the cloud-cluster-scale convective systems that comprise the ITCZ, f is not negligible. On an aqua-planet, convection must occur somewhere, given the presence of radiative cooling and surface sensible- and latent-heat fluxes, both of which act to destabilize the atmosphere. Convection releases latent heat to heat up the atmosphere to compensate for radiative cooling. Convection, or the ITCZ, occurs at the latitude where the atmosphere is most unstable: i.e., at a latitude where $\partial\omega^2/\partial\phi = 0$, where ϕ is latitude. This means that the ITCZ occurs at the latitude where $\partial f^2/\partial\phi$ $(= 8\Omega^2 \sin\phi \cos\phi)$ is balanced by $-\partial(\alpha^2N^2)/\partial\phi$ and a frictional term.

Unfortunately, it remains a challenge, if not an impossibility, to obtain an analytic expression for $\partial(\alpha^2N^2)/\partial\phi$. For the stability of individual clouds, N^2 equates to $g\partial ln\theta/\partial z$, where θ is the potential temperature (or the equivalent potential temperature for a saturated atmosphere); but for the cloud-cluster-scale convective circulations that are the constituents of the ITCZ, N^2 should be the vertical stability for cloud-cluster-scale convective systems. In a GCM, N^2 is related to the condition that allows the cumulus parameterization scheme to operate. However, the value of α is not known analytically. In fact, α has a spectrum of values, because the horizontal size of a convective system can vary from that of a synoptic system to that of the Hadley/Walker cell. Thus, α^2N^2 has no simple tractable analytic expression. Therefore, one has to rely on model experiments and qualitative arguments to push the investigation forward.

The gradient $\partial f^2/\partial\varphi$ can be identified as the forcing due to the attractor at the equator caused by inertial stability (i.e., the first effect of the earth's rotation), and $-\partial\alpha^2N^2/\partial\varphi$ can be identified as the forcing due to the attractor at one of the poles due to the latitudinal gradient of f-modified surface fluxes (i.e., the second effect of the earth's rotation.) (Note that surface sensible- and latent-heat fluxes affect the vertical profiles of temperature and moisture, which are related to N^2.) The first forcing is equal to $8\Omega^2 \sin\phi$ $\cos\phi$, and is represented in Figure 3 as curve A (positive being southward); the second forcing is represented as curve B (positive being northward) in a manner consistent with experimental results. Since curve A has a known analytic form and does not depend on the model design, it is easily understood. As mentioned before, curve B has no simple analytic expression. How curve B can be determined from an experiment will be explained in subsection 3.3.

Curve B depends on the way $\alpha^2 N^2$ is affected by the model design and in particular by the design of the model physics. Since curve B represents the attraction on convective systems due to the attractor at one of the poles through the second effect of f, it should be zero at the pole, the center of the attractor. Also, curve B depends on the gradient of f (recall that curve B is the latitudinal gradient of $\alpha^2 N^2$, and that N^2 is affected by the f-modified surface fluxes)--i.e., it depends on β. This should give curve B a maximum at the equator. However, since a convective system is fairly sizeable when it is close to the equator, the attraction by the other pole must be operating and curve B must be zero at the equator, where the attractions due to both poles cancel. Therefore, curve B has a maximum close to equator. This is shown in Figure 4, with the dashed curve being the attraction due to the second effect of f and the solid curve, curve B, being the running average of the dashed curve, with an averaging window the size of a tropical synoptic system.

In Figure 4, the dashed curve shows a rapid drop in the subtropics. We have not explained this before; here, we offer two possible explanations. First, the existence of convection means $\omega^2<0$, which requires, through Eq. (1), that $\alpha^2 > (f^2+|F|)/|N^2|$. Since the vertical scale of the circulation between the ITCZ and the equator is at the scale of the troposphere, this condition on α^2 (α is the ratio of the horizontal wave number to the vertical wave number, or the ratio of the vertical scale to the horizontal scale of the convective cell) puts an upper limit on the distance between the equator and the ITCZ, or how far the ITCZ can be away from the equator. However, this distance, or maximum latitude for the ITCZ is difficult to quantify, since N^2 cannot be easily quantified.

The other possible explanation for the rapid drop in the subtropics of the dashed curve in Fig. 4 is that if the ITCZ is far away from the equator, the conservation of absolute angular momentum in the meridional circulation in the upper troposphere between the equator and the ITCZ leads to a large latitudinal wind shear, which means within the latitudinal range of the Hadley cell, there is a large vertical wind shear. Such a large vertical wind shear in turn means there is a large latitudinal temperature gradient in the mid-troposphere. The greater the distance between the equator and the ITCZ, the greater the maximum latitudinal temperature gradient. Because the radiative equilibrium temperature, toward which the temperature is forced, is globally-uniform, the maximum latitudinal temperature gradient has a limit, and this limit imposes an upper limit on the maximum latitude the ITCZ can reach.

Either of the above two possible explanations, if true, means that the definition of curve B should be modified to include the limit on the highest latitude the ITCZ can possibly reach.

3.1.3 Dependence on the model physics

The dependence of curve B on the cumulus parameterization scheme is illustrated in Figure 3. B_{RAS} and B_{MCA} represent curve B when RAS and Manabe's moist convective adjustment (MCA) scheme are used, respectively. B_{RAS} is larger than B_{MCA}.

This is the result of the MCA scheme being subject to a more restrictive condition—i.e., the saturation requirement--in order for it to operate. Also, when the MCA scheme is used, the convective cell tends to be more concentrated and has a higher circulation speed. This gives the Coriolis force less time to act on the surface wind, thus making the second effect of the Coriolis parameter smaller than when RAS is used.

When the boundary-layer relative humidity is required to be greater than a critical value in order for RAS to operate, and this critical value is increased from 90% to 95%, curve B can change from B_{RAS} to B_{MCA}. At 90%, this criterion does not restrict RAS, but at 95%, the restriction is strong enough to make RAS behave more like MCA. MCA requires both neighboring levels to be saturated in order for it to operate, and thus is quite restrictive. In Figure 3, as curve B transitions from B_{MCA} to B_{RAS}, the location of the intercept between curve A and curve B--i.e., the location of the ITCZ--remains at the equator until the slope of curve B at the equator exceeds that of curve A at the equator. Then, the equator is no longer a stable equilibrium location, and the ITCZ jumps to the latitude of the other intercept, P. This jump is very fast, because the ITCZ is pulled by the large difference between the two curves in a “free fall.” On the other hand, when curve B decreases from B_{RAS} to B_{MCA}, point P, or the ITCZ, moves gradually toward the equator until the peak of curve B drops below curve A. At this moment, P disappears and the ITCZ jumps toward the equator; but in this case, the difference between the two curves is much smaller than in the case of ITCZ jumping away from the equator, which involves a rising curve B. Thus, the move back to equator is not as abrupt.

These deductions are borne out in aqua-planet experiments with a globally-uniform SST, as shown in Figure 5a (from Chao and Chen 2004), where the boundary-layer relative humidity criterion is held at 90% for the first 200 days and is changed linearly in time to 95% over the next 100 days, and is then kept unchanged for the remainder of experiment. Figure 5b shows the results of an identical experiment, except that the values of 90% and 95% are switched.

3.2 A retrospective of previous ITCZ theories

Some previous ITCZ theories were introduced in section 2. None of them discussed the dependence of the simulated ITCZ on the cumulus parameterization scheme. Charney's ITCZ theory (Charney 1971) was based on an axisymmetric version of his tropical cyclogenesis theory of conditional instability of the second kind (CISK). This results in a poleward forcing on the ITCZ. Charney also invoked an equatorward forcing on the ITCZ due to the higher equatorial moisture content. Under an aqua-planet with globally- and temporally-uniform SST and solar angle settings, his second forcing does not exist, and thus his theory would yield ITCZs at the poles. This is inconsistent with Sumi's aqua-planet experimental results, which yield a single ITCZ at the equator or a double ITCZ straddling the equator. Thus, Charney's first forcing is either incomplete or incorrect.

One reason that Charney's ITCZ theory fails is that the CISK theory attributes convection to boundary-layer frictional convergence.[1] The real cause of convection is vertical instability in the presence of rotation: i.e., $\omega^2 < 0$, with ω defined in Eq. (1). The

[1] Charney realized the problem with the CISK theory in the last years of his life (Arakawa, personal communication).

boundary-layer frictional convergence, on which the CISK theory depends, is the effect of convection rather than its cause. Another reason for Charney's theory's failure is that he did not recognize the second effect of the earth's rotation on convection (described in subsection 3.1.2), i. e., *the latitudinal gradient of tangential surface wind-evaporation feedback*. These two problems also exist in ITCZ theories proposed by Holton et al. (1971), Lindzen (1974), and others, which are offshoots of Charney's theory. The CISK theory is also invalid for tropical cyclogenesis Emanuel et al. (1994). However, one component of the CISK theory—the interaction between cumulus-scale convection and cyclone-scale convection—remains valid.

3.3 Aqua-planet GCM studies of the ITCZ with latitudinally-varying SST

In the presence of latitudinal variation in the SST, the latitudinal location of the ITCZ is determined by the balance between the forcings due to the SST latitudinal peak and the earth's rotation. For simplicity, a Gaussian SST latitudinal profile of global scale has been used (Eq. (1) of Chao 2000). Experiments were performed without the earth's rotation using an aqua-planet GCM with a zonally-uniform SST and a Gaussian SST latitudinal profile. When the SST profile was moved north and south while keeping its Gaussian shape, the ITCZ closely followed the latitude of the SST peak, but with a slight poleward offset (Fig. 11 of Chao 2000). This offset was zero when the SST peak was at the equator and grew when the SST peak was moved poleward, but it remained small. The reason for this offset is that when the SST Gaussian peak is away from the equator, the geometry of the aqua-planet is not symmetric with respect to the peak of the SST latitudinal profile. Also, the averaged SST poleward of the SST peak is greater than the averaged SST on the other side of the SST peak. Therefore, the ITCZ is located slightly poleward of the SST peak. At this latitude is the center of an ITCZ attractor due to the SST peak, and its associated attraction as a function of latitude can be represented by a straight line crossing this latitude, due to the global size of the SST latitudinal profile--at least in the neighborhood of this latitude.

When the earth's rotation is restored, the ITCZ latitudinal location is determined by the balance between the rotational attractor and the SST peak attractor. Figure 6 (from Chao et al. 2007) shows the two types of attractions schematically. Attraction R, due to earth's rotation, is the difference between curves A and B (i.e., R=A-B) in Figure 3. Curve R—where a positive value represents southward attraction--takes on different forms depending on the model physics, of which the cumulus convection scheme is the most important. When a stringent scheme--such as MCA, as described in subsection 3.1.3--is used, curve R is represented by the long-dashed curve. When a less stringent scheme such as RAS is used, curve R is represented by the dotted curve. Curve R can change to something between or beyond these two curves when the model physics is changed.

Figure 6 also shows the attraction due to the SST peak, represented by line S, when a Gaussian SST latitudinal profile is used and the SST peak is located at the equator. Since the SST latitudinal profile is global, the attractor it creates has a simple structure and thus can be represented by a straight line in the tropics. If the model physics is such that curve R takes on the shape of either the long-dashed or the short-dashed curve in Figure 6, the ITCZ is located at the equator. If curve R is the solid curve, the equator and 13°NS are stable solutions for the ITCZ: i.e., three ITCZs are obtained. This actually happened in an experiment reported by Chao and Deng (1998), the dotted curve of their Figure 6. If curve R is the dotted curve in Figure 6, a double ITCZ occurs.

The way Fig. 6 was constructed is as follows. Line S is first plotted with an arbitrary slope. Next, one follows the results of the experiment where the SST Gaussian profile is slowly moved north and south, and line S is moved slowly north and south accordingly without changing its slope. The latitude where the ITCZ exists is the latitude where curve R intersects line S. As line S is moved north and south, curve R is traced from the results of the experiment. (Note that this method of determining curve R is an approximation; see Appendix B of Chao et al. (2007) for details of this approximation.) Once curve R is obtained, curve B in Fig. 3 can be obtained from the relationship R=A-B. A is known analytically as explained in Section 3.1.

When the SST latitudinal Gaussian profile is retained and the entire profile is moved north and south in an annual cyclic manner, the latitude of the ITCZ changes. If curve R is the long-dashed curve in Figure 6 and the SST peak is moved away from the equator--i.e., line S is moved toward the north pole while retaining its slope--the ITCZ is initially at the equator and follows behind the SST peak; then it suddenly jumps poleward, but ultimately fails to catch up with the SST peak. Thus, for the long-dashed curve R, the ITCZ is always equatorward of the SST peak and only a single ITCZ is possible. This is not consistent with what is observed. If curve R is the dotted curve in Figure 6, since the observed SST peak does not move too far (>10°) away from the equator, a double ITCZ always exists. This is not realistic either. The more realistic curve R is one close to the solid curve in Figure 6. It allows a double ITCZ when the

SST peak is close to the equator and a single ITCZ when the SST is moved more than 5° away from the equator.

3.4 The origin of systematic errors in GCM-simulated ITCZ precipitation over the ocean

As explained in the preceding subsection, if curve R is the dotted curve in Fig. 6, a double ITCZ always exists if the SST peak does not move more than 10° away from the equator. As the SST peak moves away from the equator all the way to 10°N, the southern component of the double ITCZ remains and becomes stronger, resulting in a false double ITCZ throughout the season, with a stronger southern component in the June-July-August season. This occurs often in GCMs (e.g., Wu. et al. 2003, Zhang and Wang 2006, Bacmeister, et al. 2006.) The reason that the southern component of the false double ITCZ is stronger than the northern component in the JJA season is as follows. In an approximate sense, there is a height-zonal partition surface separating the northern general circulation from the southern general circulation, and as the SST peak moves north of the equator, this partition surface moves north also. As a result, the tropical area south of the partition surface becomes larger, and since the latent heat released in the southern ITCZ now has to compensate for the radiative cooling of a larger tropical area, the southern ITCZ must be stronger.

Since in a GCM, curve R relative to line S can take on a spectrum of shapes depending on the model design, as presented in Figure 6, the systematic errors in ITCZ simulation can correspondingly vary. If curve R relative to line S has the shape of the long-dashed curve, since the observed SST peak does not move more than 10° north of the equator, the ITCZ is close to the equator year-round. Only when curve R takes on a shape between the short-dashed curve and the solid curve in Fig. 6 does the GCM yield reasonable annual cycle of ITCZ latitudinal location.

As described in subsection 3.1.3, curve B in Figure 3 and therefore curve R in Figure 6, can be adjusted by changing the critical value that the boundary-layer relative humidity must exceed before RAS can operate. Thus, it is not difficult to tune the model such that the ITCZ simulation becomes reasonable in a particular region. Since in different regions, the SST latitudinal distribution is different, the slope of line S is also different. Therefore, the value of the tuning parameter in different regions may have to be different. However, even if the ITCZ behavior is tuned well by using different values for the tuning parameter in different longitudinal segments, that still may not be a good solution. That is because the GCM simulation involves a great deal more than just simulating the ITCZ. Other tropical phenomena, such as the MJO and equatorial waves, may become worse as a result of tuning the ITCZ. Therefore, picking one particular aspect of the model physics to modify or to tune in hopes of improving the ITCZ simulation may result in adverse side-effects in other aspects of the GCM simulation. These adverse side-effects can only be avoided if all aspects of the model physics with the exception of the aspect being modified or tuned have already been modeled with high fidelity--a situation that is not going to happen for the foreseeable future. Thus, to improve the model performance, one should study many more atmospheric phenomena besides the ITCZ. More details about this section are given in Chao et al. (2007).

3.5 Dependence of GCM-simulated ITCZs on a model's horizontal resolution

One of Sumi's (1992) experiments using a globally-uniform SST showed that a single ITCZ over the equator became a double ITCZ straddling the equator when the model's horizontal resolution was doubled. The explanation for this is that as the model's horizontal resolution is doubled, the horizontal size of the synoptic-scale convection decreases. This size decrease increases α in Eq. (1), which results in a larger curve B and changes curve R in the direction from the long-dashed curve toward the dotted curve. As a result, the single ITCZ over the equator becomes a double ITCZ straddling the equator. However, the increase in α is also accompanied by a weakened increase in N due to the smaller size of the convective system. This decreases the evaporation due to the faster convective circulation, which limits the time an air parcel spends between the downdraft and the updraft. Thus, our interpretation needs further refinement.

The above interpretation indicates that as the model horizontal resolution is changed, the model physics is essentially changed. This is a quite undesirable result, since increasing the horizontal resolution is expected to give the simulation more detail but not change its gross characteristics. Hence, it is important that grid-size-dependent physical parameterization schemes be developed Jung and Arakawa (2004).

3.6 Some remaining questions regarding the aqua-planet study of the origin of the ITCZ

There are a number of remaining problems with the study of the ITCZ using an aqua-planet model. Under globally- and temporally-uniform SST and solar angle settings, sometimes only one component of a double ITCZ exists. This experimental result was encountered by Pike (1971), Raymond (2000), Chao (2000), and Barsugli et al. (2005) (but not by Sumi 1992). This is likely due to some kind of instability so that the two components give way to one component; but the nature and the onset criterion of this instability are unknown. This equatorially-asymmetric ITCZ in atmospheric models is believed to contribute to the equatorial asymmetry in coupled ocean-atmosphere models with globally-uniform settings Barsugli et al. (2005).

Note that when the ITCZ is at the equator in the case where boundary-layer relative humidity must be >95% in order for RAS to operate, there are secondary precipitation regions around 25° north and south of the equator (Figure 5). This has not been explained. A possible explanation is that these secondary precipitation regions might be the remnants of Benard cells that are not completely annihilated by the earth's rotation. Also note that in Fig. 5b, the equatorial ITCZ occasionally splits into two. The reason for this split is another unknown; but in a time-mean sense, the equatorial ITCZ is a single ITCZ over the equator. The explanation of how ITCZ forms by Chao and Chen (2004) based on the latitudinal gradient of ω^2, as reviewed in section 3.1, may be only a simplified version of a more general theory yet to be discovered.

4 THE ORIGIN OF MONSOONS

The monsoon is a time-mean (e.g., monthly-mean) continental-scale rainy region in the tropics with an associated wind circulation that extends over a much larger area than the rainy region. The basic features of a monsoon are heavy rainfall and southwesterly (northwesterly in the southern hemisphere) surface winds. These, again, are time- (e.g., monthly-) mean features. At any instant, rainfall is concentrated in a few convective systems, and a station in a monsoonal region can even have clear skies between rainy days. Also, winds can blow from any direction. Another salient feature of a monsoon is its vertical wind shear. The vertical wind shear (in a time-mean sense) in a monsoon is the largest in the tropics. This has led some researchers to use time-mean vertical wind shear instead of precipitation as an index of monsoon intensity Webster et al. (1998). The most intense monsoon is the South Asian monsoon. There are also Australian, African, Central American-Mexican (also known as the North American), and South American monsoons. The origin of monsoons has, for more than three hundred years, been attributed to land-sea thermal contrast on a continental scale, as proposed by Halley (1686). According to this theory, the heating of a continent in the summer induces convergence toward the land, which brings moisture from the surrounding ocean--like a giant sea breeze. This converging air is modified by the Coriolis force and is made to turn toward the northeast (in the northern hemisphere), giving rise to the familiar monsoonal southwesterly flow Holton (2004).

A quick look at the monthly-mean precipitation associated with the Australian monsoon (see the January and February panels of Figure 2, which show monthly-mean precipitation averaged over a 20-year span) reveals that the rainy region covers a longitudinal domain many times that of the Australian continent. If land-sea thermal contrast were the cause of the Australian monsoon, the rainy region should not stretch so far away from the Australian continent, and it should curve around the edge--if not the whole--of the continent. This indicates that land-sea thermal contrast on a continental scale is not a necessary condition for a monsoon to form. This is not to say that land-sea thermal contrast plays no role in the formation of monsoons, however, because it does have a modifying effect, and indeed, is quite dominant, in causing the South American monsoon.

If land-sea thermal contrast is not the basic cause of monsoons, what is? The answer lies in what a monsoon is. A monsoon is no more than an ITCZ located sufficiently (e.g., >10°) away from the equator during its annual latitudinal cycle of movement. The movement of an ITCZ away from the equator is not steady; it makes a poleward jump of 5° to 7° within just a few days. The ITCZ after this jump is located far enough away from the equator to be strongly influenced by the effect of the Coriolis force and to develop the familiar monsoonal southwesterlies in the NH and northwesterlies in the SH at the surface. Figure 7 shows the wind structure of the Gill solution Gill (1980), see his Figure 3, modified in such a way that the heating source is stretched in the zonal direction. It shows southwesterlies forced by an asymmetric (with respect to the equator) heating source. In light of foregoing, it is clear that *during its annual cycle of latitudinal movement, an ITCZ, after its poleward jump, is a monsoon, and the jump itself equates to the monsoon onset*. (We will review the physical mechanism of monsoon onset in the next section.) Now, with a clear understanding of what a monsoon is, we can assert that the cause of monsoons is the cause of the ITCZ, which we discussed in section 3.1 with respect to an aqua-planet setting with globally- or zonally-uniform SST. A monsoon can thus exist on an aqua-planet Yano and McBride (1999).

In the real atmosphere, because of land-sea distribution and variation in the SST, the ITCZ is not zonally-uniform but breaks into segments. The ITCZ prefers longitudinal regions of high SST, as in the western Pacific and Indian Ocean, and regions of landmass surrounded by oceans of low SST, as in South America and Africa. In regions of high SST, the ITCZ is interrupted by landmass. For example, in Figure 2, the ITCZ in the western Pacific and Indian Ocean in northern summer (the South Asian summer monsoon) is interrupted by Indochina and India.

The above explanation of the cause of monsoons, proposed by Chao and Chen 2001b, is supported by GCM experiments. In one of their experiments, Chao and Chen replaced the Asian and Australian continents with oceans of SST taken from surrounding ocean edges of the same latitude, and were able to simulate the South Asian and Australian monsoons. They used the NASA/Goddard GCM (version GEOS-2) with a 4ºx5° latitude-longitude horizontal resolution and 17 vertical levels. The model used the RAS cumulus parameterization scheme. Figure 8 shows the result of precipitation averaged over the last three Augusts in two four-year integrations. It shows the results of experiments with and without the Asian and Australian landmasses. Figure 8b shows that the South Asian monsoon precipitation region still exists without the Asian landmass. Since its publication, the Chao and Chen (2001b) interpretation of the origin of monsoons has gained support Gadgil (2002), Prive and Plumb (2007.)

5 THE ORIGIN OF MONSOON ONSET

As mentioned in the previous section, a monsoon onset is the jump of an ITCZ away from the equator. This is particularly clear for the West African monsoon (e.g., Sultan and Janicot 2003). The physical mechanism of monsoon onset can be understood by understanding the forcings on the ITCZ. Figure 3 describes the forcings due to the earth's rotation. The net forcing on the ITCZ due to the earth's rotation, represented by curve R, is the difference between curve A and curve B in Figure 3 (i.e., R=A-B). When MCA is used as the cumulus parameterization scheme, curve R is depicted as the long-dashed curve in Figure 6. Line S represents the forcing due to the SST peak, which crosses the horizontal axis at a latitude very close to the SST peak itself. An aqua-planet experiment without the Coriolis force but with a Gaussian SST latitudinal profile (Eq. (1) of Chao 2000) yields an ITCZ very close to the peak of the SST--but not exactly at it--when the SST peak is away from the equator (Fig. 11 of Chao 2000.) Line S, drawn as a straight line, is an approximation, since the SST Gaussian latitudinal profile is on a global scale. In the case where MCA is used, the monsoon onset does not take place until the SST peak is fairly far away from the equator, or when the season is far into the summer. This is certainly not realistic. Also, with MCA, the monsoon onset is less abrupt than the monsoon retreat, as seen in Fig. 8b of Chao (2000).

These unrealistic features vanish when MCA is replaced by RAS with proper tuning. The reason for this can be seen in Figure 6, which shows that curve R can take on various shapes, depending on the model physics. Figure 6 shows that when curve R is somewhere between the short-dashed curve and the solid curve, the ITCZ is at the equator when the SST peak is also there. When the SST peak is moved to 7°N, the ITCZ is at 4°N, and a further northward movement of the SST peak will bring about a jump of the ITCZ to about 11°N. Also, this optimal curve R yields a more abrupt monsoon onset than monsoon retreat. Thus, model modifications should move curve R to somewhere between the short-dashed curve and the solid curve in Figure 6, in order to achieve a good simulation of a monsoon onset.

6 **MONSOON NOMENCLATURE**

The term monsoon is familiar to most people; but, surprisingly, its usage is not always consistent. Once we have understood the equivalence between a monsoon and an ITCZ that is sufficiently displaced from the equator, it is easy to understand that the term "East Asian summer monsoon" is a misnomer. The "East Asian summer monsoon" refers to the rainy region in southeast China from May to August. This rainy region is associated with the Mei-yu front, which stretches from southern China to Japan and its vicinity. This front is the middle-latitude storm track. It arises because of middle-latitude planetary-scale topography and continental-scale land-sea thermal contrast, which are clearly different from the cause of the ITCZ. To also call it a monsoon is to give two distinct physical processes the same name, thus creating confusion. There are other inconsistencies with this name. A similar rainy region in the southeast U. S. stretching into the Atlantic is not called a monsoon. Thus, the term "East Asian summer monsoon" should be abandoned. It could better be called the east Asian middle-latitude storm track. The origin of the term "East Asian summer monsoon" probably has to do with the seasonal nature of this phenomenon. However, many atmospheric phenomena have a seasonal cycle; they cannot all be called monsoons.

7 SUMMARY AND POSSIBLE FUTURE RESEARCH DIRECTIONS

We have reviewed how the ITCZ originates by presenting theoretical arguments and experiments using an aqua-planet model. The ITCZ can be generated in an aqua-planet model with either the earth's rotation or a latitudinal peak in the SST. However, since both of these two elements exist in an aqua-planet model, the ITCZ's latitudinal location is determined by the balance of the forcings exerted by them. The forcings generated by these two elements are summarized in Fig. 6. In this figure, line S represents the northward forcing on the ITCZ due to the peak of the SST latitudinal profile, assuming a Gaussian profile. Curve R represents the southward forcing on the ITCZ due to the earth's rotation--which takes on various forms, depending on the cumulus parameterization scheme being used. The solid curve R in Fig. 6 is closer to nature than the other curves. The intersection(s) between line S and curve R is (are) the location(s) of the ITCZ. Curve R is the sum of two components: one arises from the inertial stability and the other arises from the increased evaporation due to the tangential surface wind generated by the earth's rotation. The second component depends on the cumulus parameterization scheme, whereas the first component does not. Besides the cumulus parameterization scheme, the interactions between convection and radiation, and between convection and surface fluxes, also have an impact on the second component. In a full GCM or in the real atmosphere, landmass and the SST distribution break the ITCZ into different longitudinal segments. The ITCZ prefers longitudes of high SST or landmass with low surrounding SST. The seasonal latitudinal movement of the ITCZ is not always smooth; there is a jump when it moves away from the equator. The ITCZ after its poleward jump is a monsoon and the jump itself is the monsoon onset. The jump back toward the equator is the monsoon retreat, and we have discussed why the monsoon retreat is less sudden than the monsoon onset. We have also reviewed why land-sea thermal contrast is not a necessary condition for a monsoon to form, contrary to the age-old belief. Furthermore, we have reviewed the inconsistencies in the term "East Asian summer monsoon."

Future research directions include solving the problems discussed in subsection 3.6. The solutions to these problems would, of course, lead to more insight into the ITCZ. How the knowledge of the origins of ITCZs, monsoons and monsoon onset accumulated thus far can be applied to improve GCMs is another important future research direction. Current GCMs have serious problems correctly simulating the annual cycle of the location and strength of ITCZs. The problems obviously reside in the model physics parameterizations, with the cumulus parameterization taking on the most prominent role. Exactly which parts of the cumulus parameterization should be revised and how to revise them are important questions. When striving to improve the GCM simulation of ITCZs and monsoons, one should also consider the oscillations within the ITCZs—the so-called convectively-coupled equatorial waves,[2] including the MJO—so that improvement in simulating ITCZs and monsoons is not accompanied by degradation

[2] A better descriptor for this term is "chimeric equatorial waves" (Chao 2007.)

in simulating these equatorial waves. Thus, the origin of these equatorial waves should be given a high priority in future research.

The aqua-planet model experiments of Chao (2000) and Chao and Chen (2001, 2004) could be used for aqua-planet inter-model comparison purposes Neal and Hoskins (2004). Comparing the performance of various GCMs in simulating monsoon onset could be a worthy endeavor for the Atmospheric Model Intercomparison Project. This suggestion is based on the fact that simulating *transitions* between quasi-equilibria, such as monsoon onset and stratospheric sudden warming Chao (1985), is more demanding on GCMs' capabilities than simulating the quasi-equilibria themselves, and thus provides a more sensitive tool to differentiate among the capabilities of various GCMs.

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Figure Captions

Figure 1. The ITCZ clouds in the eastern Pacific are shown in this NOAA GOES-West image taken on Aug. 27, 1999.

Figure 2. Monthly mean precipitation averaged from 1979 to 1998 using Xie-Arkin data for (a) the hemisphere east of 30E and (b) the hemisphere east of 150W.

Figure 3. Schematic diagram showing the strength of the attraction on the synoptic-scale convective systems that comprise the ITCZ due to the first effect of the Coriolis parameter (curve A, positive southward) and to the second effect of the Coriolis parameter (curve B, positive northward). Curve B is a function of the cumulus parameter scheme.

Figure 4. Schematic diagram showing curve B of Figure 3 as the latitudinal running mean of the magnitude of the attraction due to the second effect of the Coriolis parameter.

Figure 5. Zonal mean precipitation as a function of latitude and time in an experiment with an aqua-planet model that has a globally-uniform SST and solar angle. The cumulus parameterization scheme used is the relaxed Arakawa-Schubert (RAS) scheme and an extra condition is imposed on RAS such that the boundary layer relative humidity must be greater than a critical value for RAS to operate. In (a) the critical value is set at 90% in the first 200 days and then is changed to 95% linearly over the next 200 days and then remains at 95% thereafter. In (b) the values of 90% and 95% are switched.

Figure 6. Curve R is the net southward attraction on the synoptic-scale convective systems due to the earth's rotation (R=A-B). (Curve R is the difference between curve A and curve B in Figure 3. Shown are curves R for different cumulus convection schemes. Line S denotes the attraction due to a global scale Gaussian SST latitudinal profile with global scale with its peak at the equator.

Figure 7. Zonal running average of Gill's 1980 solution Gill's Figure 3 in non-dimensional scale (unity in length is about 3° in dimensional scale). Wind arrows and heating field (in contours) are shown. Note that the two axes are not of the same scale.

Figure 8. Monthly averaged precipitation (mm/day) averaged over three last three years of a four-year experiment using the Goddard GEOS-2 GCM with full topography (a) and with Asian and Australian continents replaced by ocean (b).

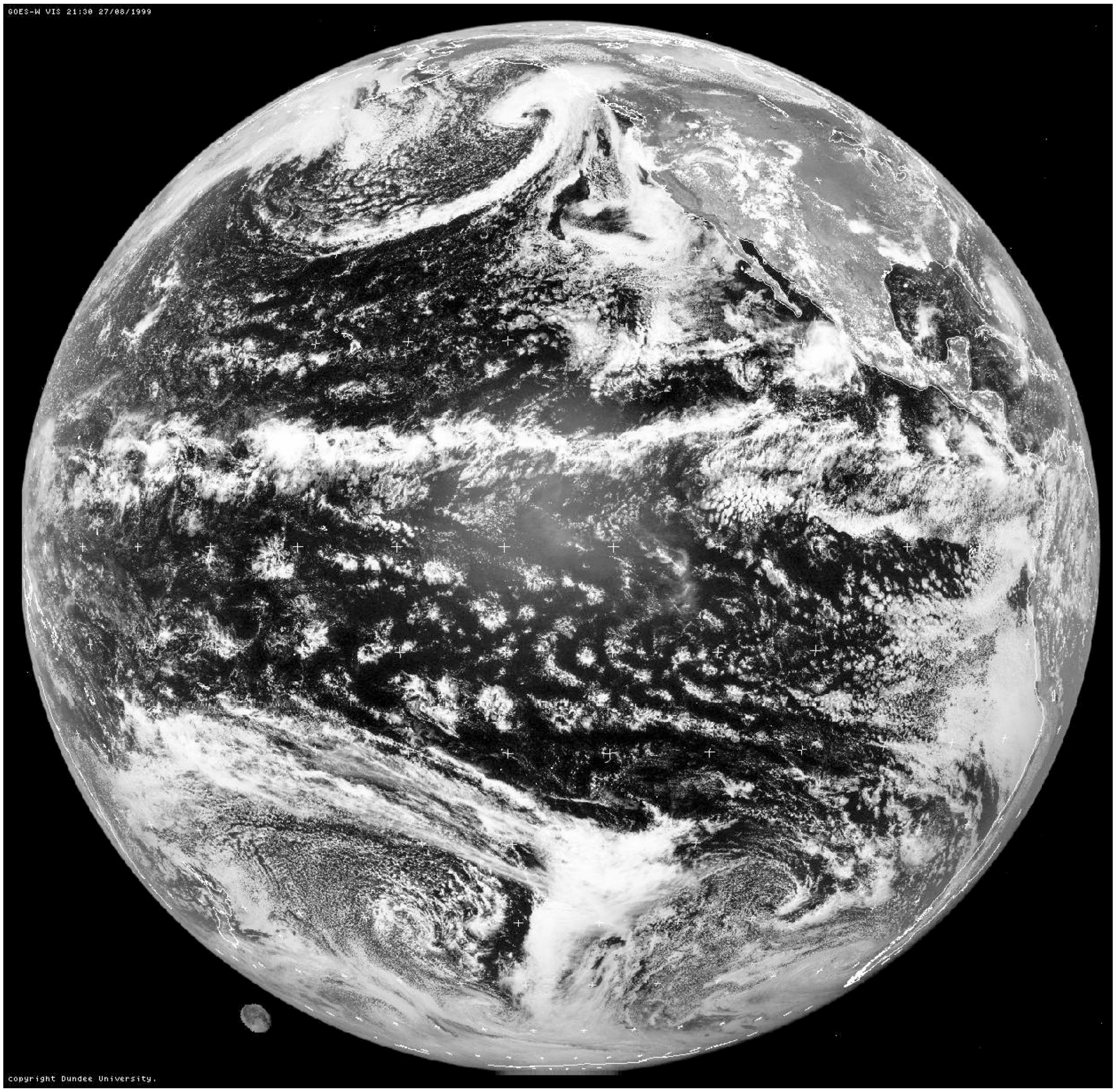


Figure 1 The ITCZ clouds in the eastern Pacific are shown in this NOAA GOES-West image taken on Aug. 27, 1999.

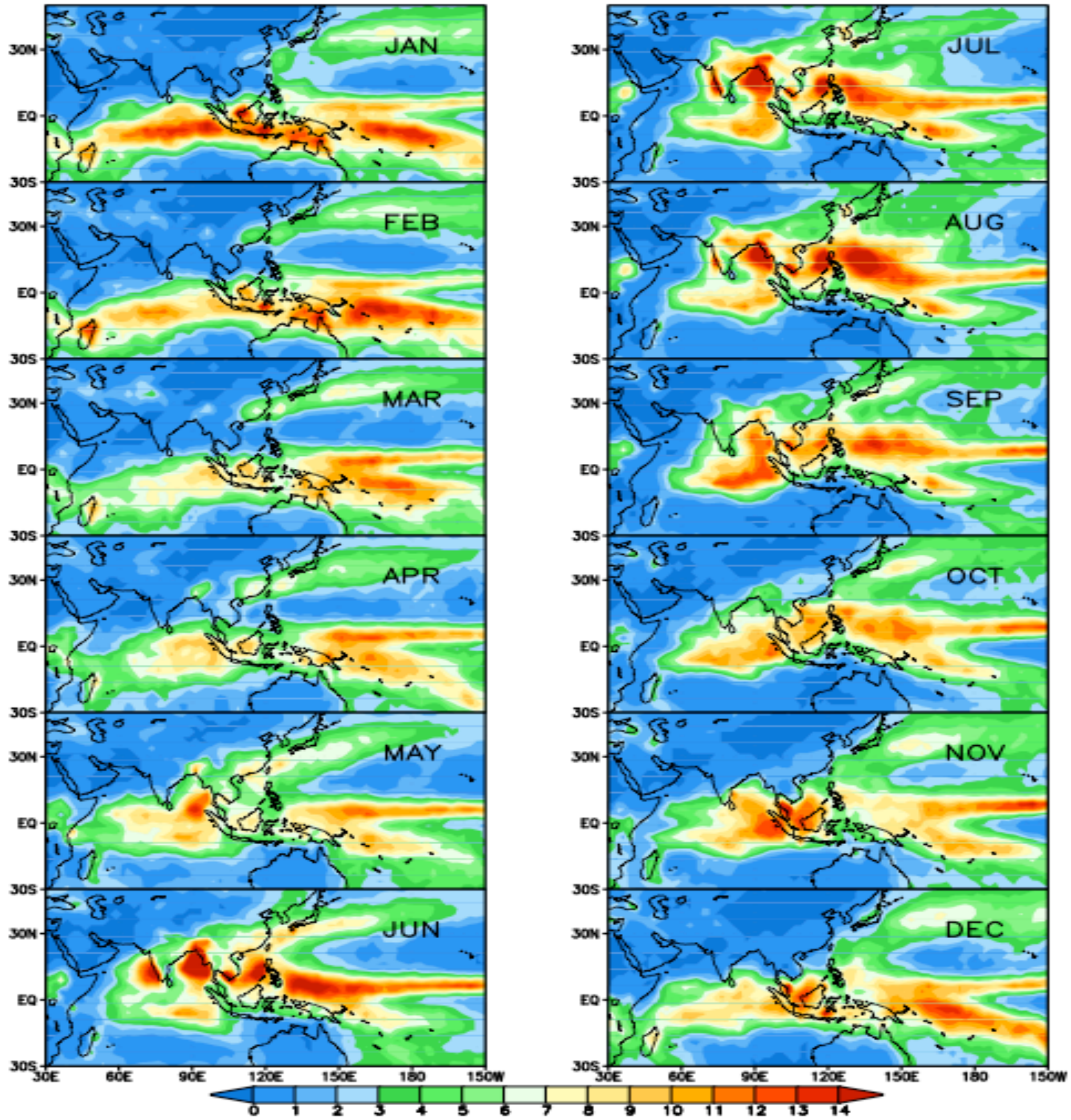
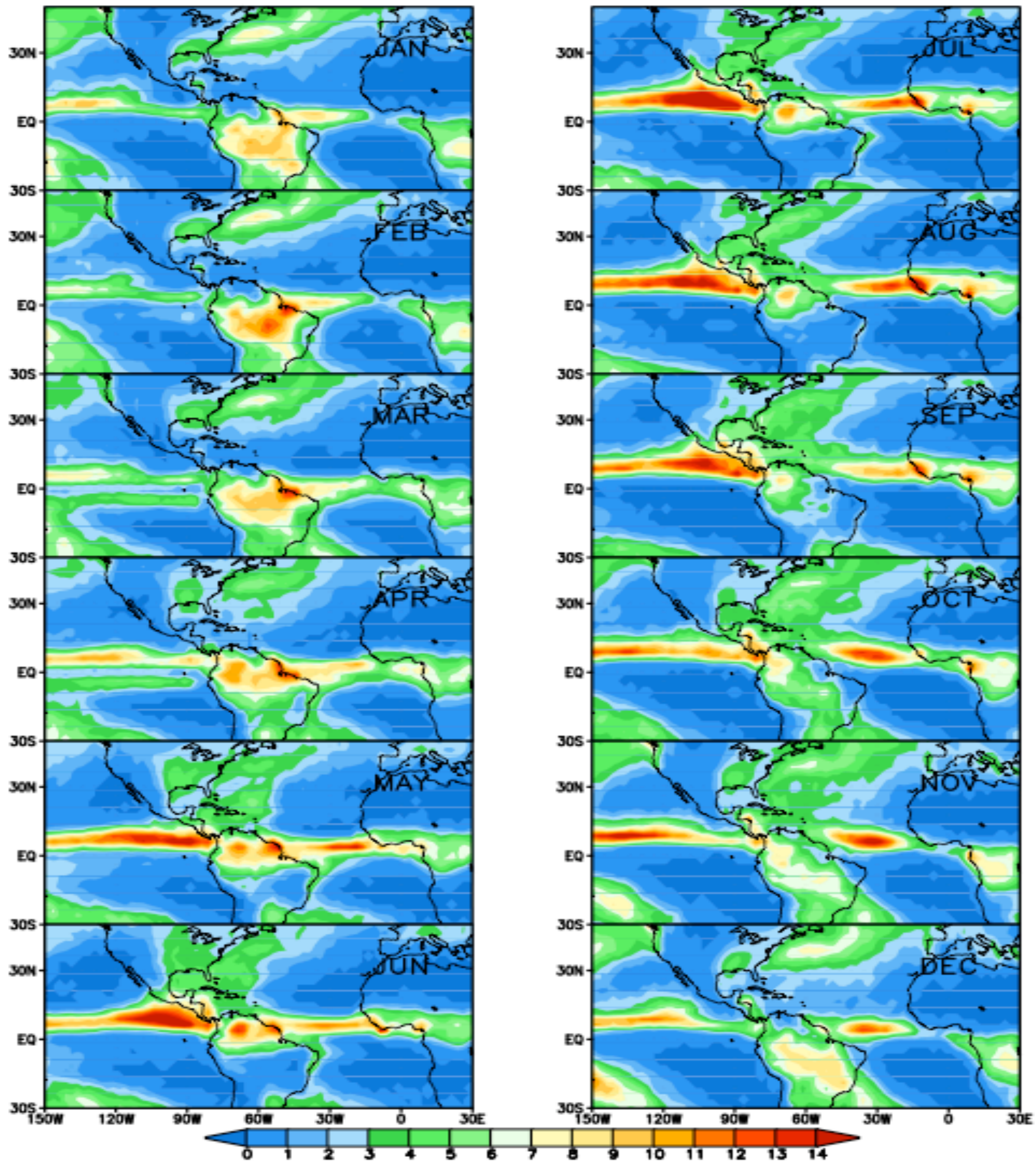


Figure 2. Monthly mean precipitation averaged from 1979 to 1998 using Xie-Arkin data for (a) the hemisphere east of 30°E and (b) the hemisphere east of 150°W.


JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
30N
EQ
30S
150W
120W
90W
60W
30W
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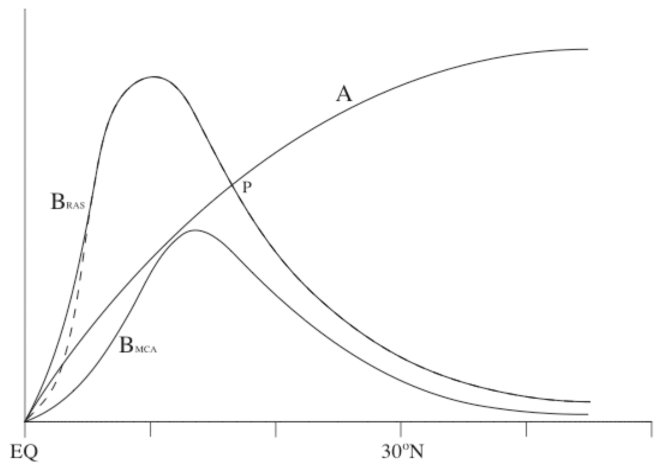

Figure 3. Schematic diagram showing the strength of the attraction on the synoptic-scale convective systems that comprise the ITCZ due to the first effect of the Coriolis parameter (curve A, positive southward) and to the second effect of the Coriolis parameter (curve B, positive northward). Curve B is a function of the cumulus parameter scheme.

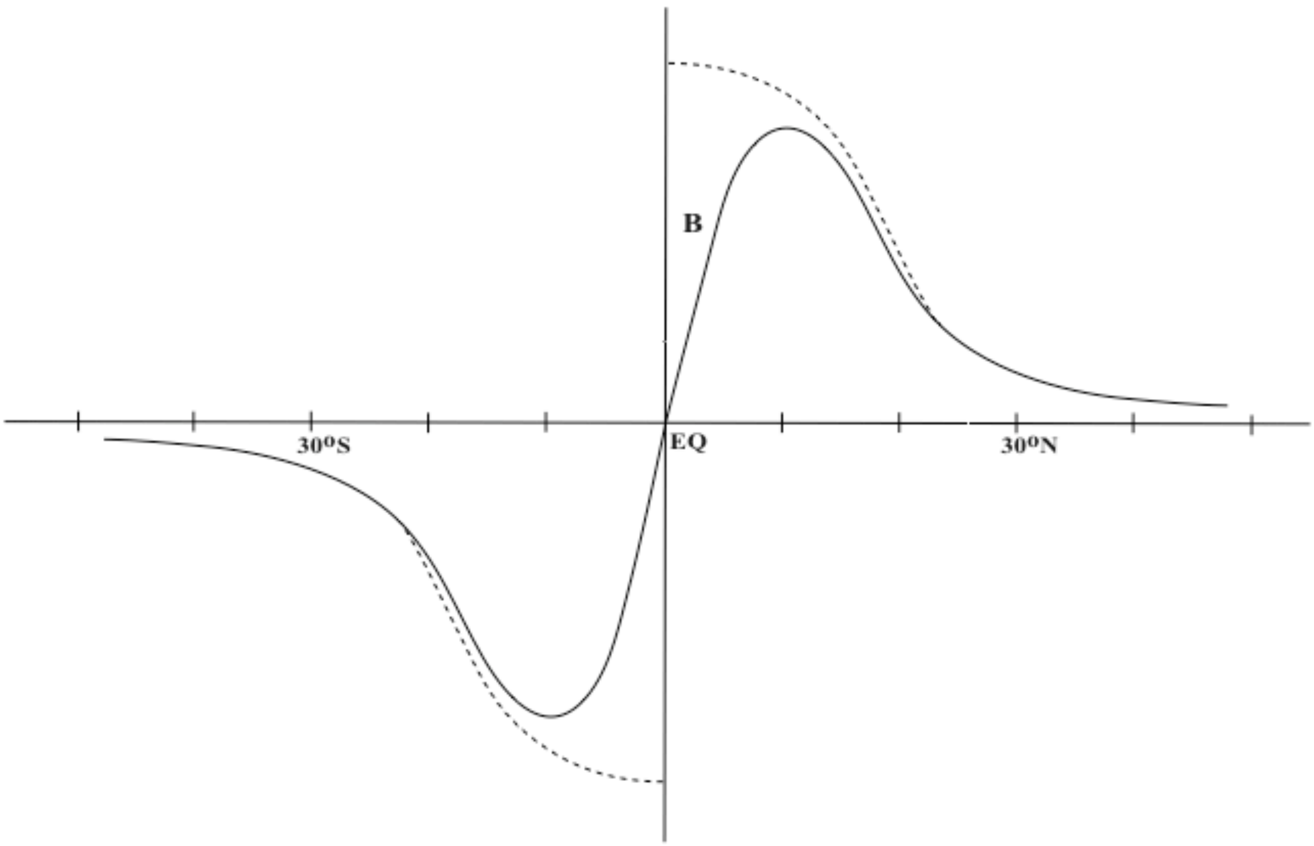

Figure 4. Schematic diagram showing curve B of Figure 3 as the latitudinal running mean of the magnitude of the attraction due to the second effect of the Coriolis parameter.

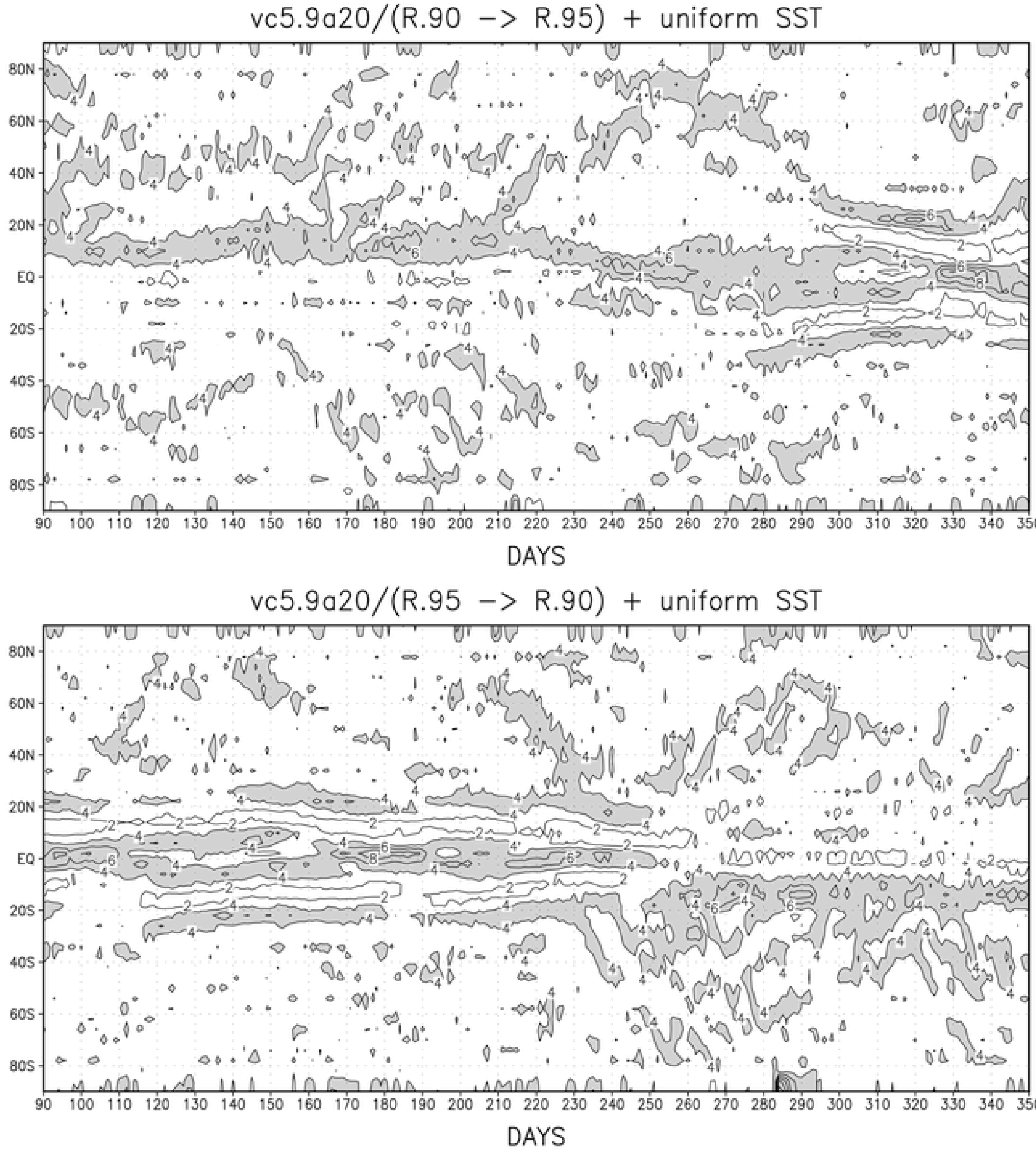

Figure 5. Zonal mean precipitation as a function of latitude and time in an experiment with an aqua-planet model that has a globally-uniform SST and solar angle. The cumulus parameterization scheme used is the relaxed Arakawa-Schubert (RAS) scheme and an extra condition is imposed on RAS such that the boundary layer relative humidity must be greater than a critical value for RAS to operate. In (a) the critical value is set at 90% in the first 200 days and then is changed to 95% linearly over the next 200 days and then remains at 95% thereafter. In (b) the values of 90% and 95% are switched.

C

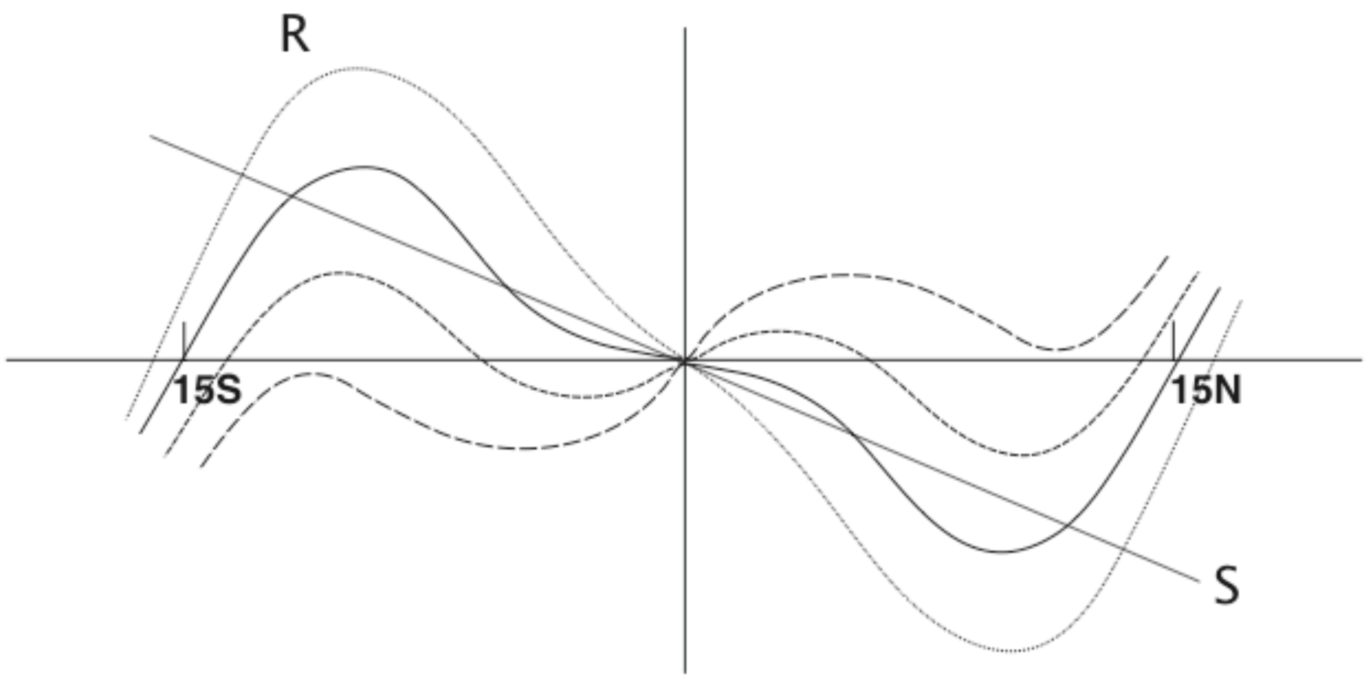

Figure 6. Curve R is the net southward attraction on the synoptic-scale convective systems due to the earth's rotation (R=A-B). (Curve R is the difference between curve A and curve B in Figure 3. Shown are curves R for different cumulus convection schemes. Line S denotes the attraction due to a global-scale Gaussian SST latitudinal profile that has its peak at the equator.

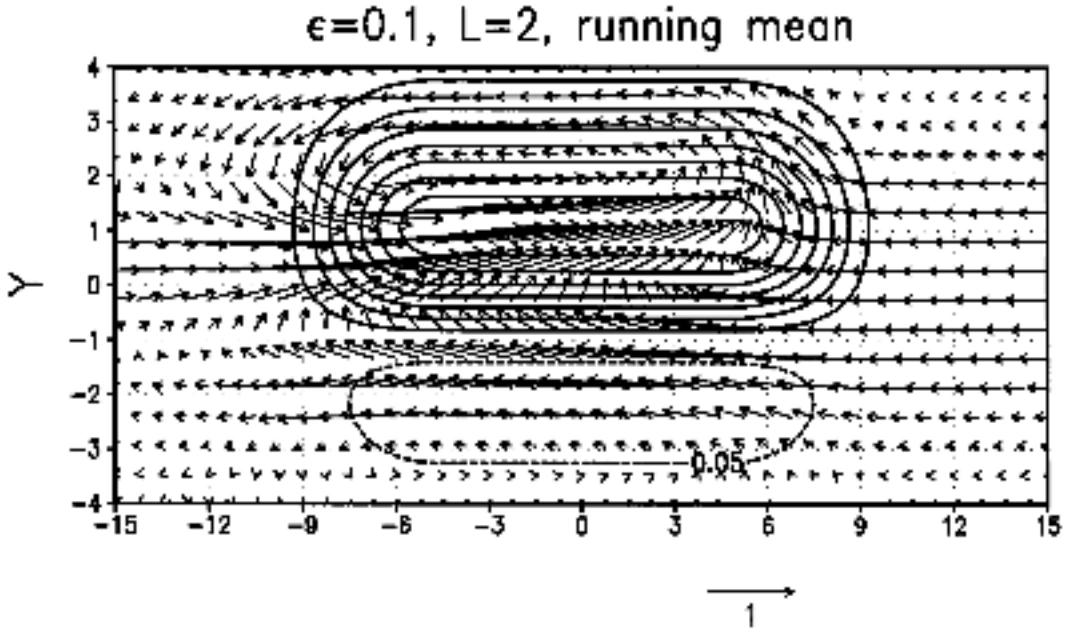

Figure 7. Zonal running average of Gill's 1980 solution Gill's Figure 3 in non-dimensional scale (unity in length is about 10° in dimensional scale). Wind arrows and heating field (in contours) are shown. Notice that the two axes are not of the same scale.

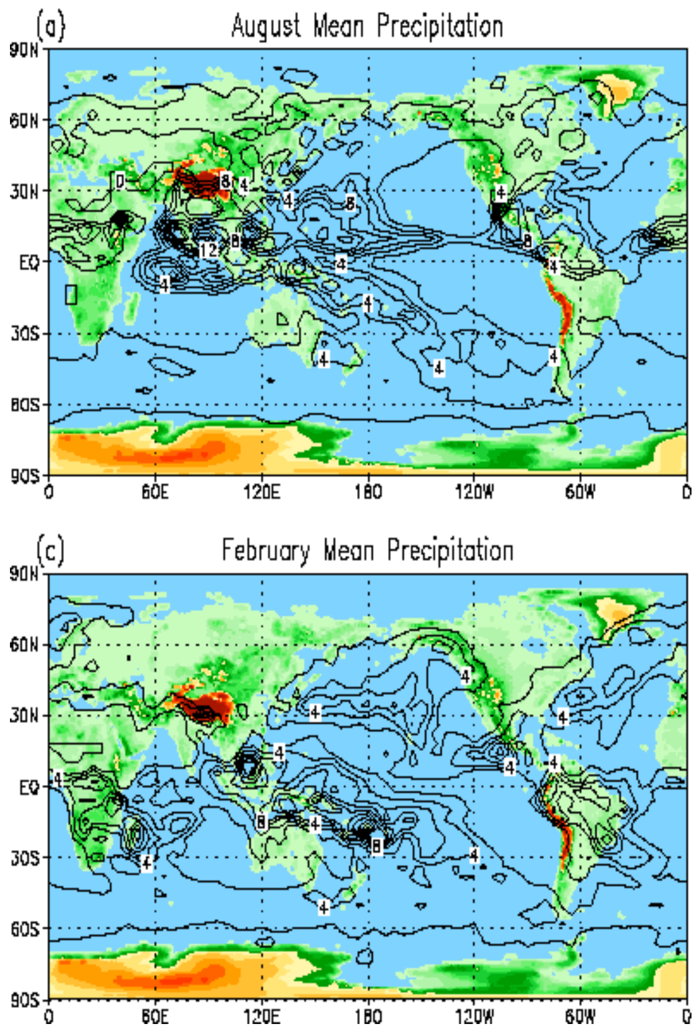

Figure 8. Monthly averaged precipitation (mm/day) averaged over three last three years of a four-year experiment using the NASA GEOS-2 GCM with full topography (a) and with Asian and Australian continents replaced by ocean (b).

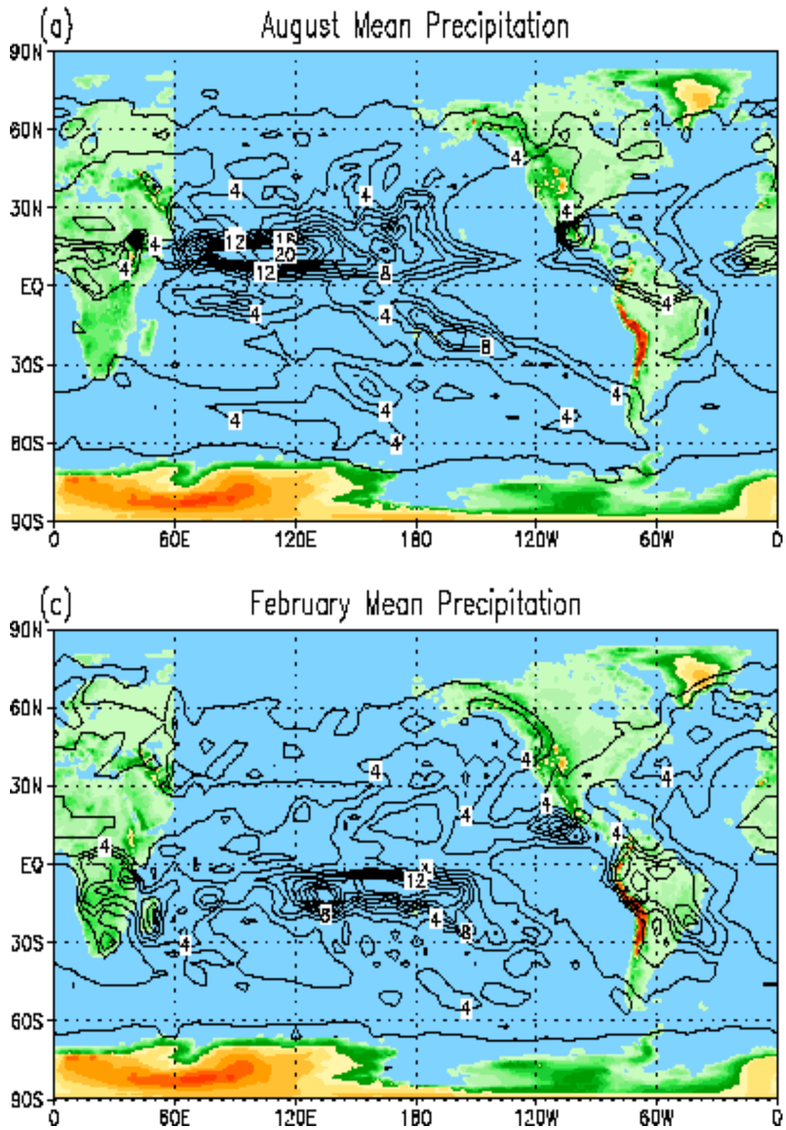

Figure 8. Monthly averaged precipitation (mm/day) averaged over three last three years of a four-year experiment using the Goddard GEOS-2 GCM with full topography (a) and with Asian and Australian continents replaced by ocean (b).