8B.3 Single and Double ITCZ in Aqua-planet Models with Globally and Temporally Uniform Sea Surface Temperature and Solar Angle: An Interpretation

Winston C. Chao and Baode Chen[1]
NASA/Goddard Space Flight Center, Greenbelt, Maryland
[1]GEST Center, University of Maryland, Baltimore County, Maryland

1. Introduction

Previous studies (Chao 2000, Chao and Chen 2001, Kirtman and Schneider 2000, Sumi 1992) have shown that, by means of one of several model design changes, the structure of the ITCZ in an aqua-planet model with globally uniform SST and solar angle (U-SST-SA) can change between a single ITCZ at the equator and a double ITCZ straddling the equator. These model design changes include switching to a different cumulus parameterization scheme (e.g., from relaxed Arakawa-Schubert scheme (RAS) to moist convectivc adjustment scheme (MCA)), changes within the cumulus parameterization scheme, and changes in other aspects of the model, such as horizontal resolution. Sometimes only one component of the double ITCZ shows up; but still this is an ITCZ away from the equator, quite distinct from a single ITCZ over the equator. Since these model results were obtained by different investigators using different models which have yielded reasonable general circulation, they are considered as reliable. Chao and Chen (2001; hereafter CC01) have made an initial attempt to interpret these findings based on the concept of rotational ITCZ attractors that they introduced. The purpose of this paper is to offer a more complete interpretation.

2. Interpretation

Under the U-SST-SA condition, as under the normal condition, the ITCZ consists of a string of convective systems along a zonal belt. These convective systems are predominantly unstable inertial gravity wave coupled with forced Rossby and Kelvin wave components. Thus as a starting point, we will look at the inertial gravity waves. According to the linear theory, convection occurs when the squared frequency of the inertial gravity wave (in an rotating atmosphere with hydrostatic approximation):

$$\sigma^2 = f^2 + \alpha^2 (g \partial \ln \theta / \partial z) + |F| , \qquad (1)$$

which is from Eq. (8.4.23) of Gill (1982), turns negative. In Eq. (1), f is the Coriolis parameter, g is the gravitational constant, α is the ratio of horizontal to vertical wave numbers, θ is the potential temperature for dry atmosphere and is the equivalent potential temperature when the atmosphere is saturated. For unsaturated atmosphere, it suffices to say that θ denotes a similar quantity. $\partial\theta / \partial z$ is the vertical stability. We have added a positive |F| term in Eq. (1) to represent the effect of friction. Our knowledge about Eq. (1) is not complete, since the exact definition of θ is not given and how θ is related to the circulation field is not completely clear. However, we do not have to use Eq. (1) in an exact way. For our purpose we only intend to point out that a convective system occurs when a not-yet-well-defined vertical instability is large enough to overcome the stabilizing effects of rotation (i.e., the f^2 term) and friction. Here we have departed from the confine of inertial gravity wave to include the other types of waves in the convective system. The fact that f^2 is a positive term and thus can cancel partially the negative second term on the right hand side of Eq. (1) means that the earth's rotation has a stabilizing effect. The dynamic reason for the stabilizing effect of rotation was explained in CC01. Thus, according to the f^2 term in Eq. (1) (i.e., if the other two terms on the right hand side did not exist) the equator is the most favored location for convection. In other words, the equator is an attractor for convection (or more precisely, the upward branch of the convective cells favors the equator), or the ITCZ. Additionally, there is a second effect of earth's rotation embedded in the second term on the right hand side of Eq. (1). The vertical instability is maintained by the high θ in the boundary layer as a result of the surface fluxes into the boundary layer as the air flows toward the precipitation centers. With a higher f, the inflow takes on a more spiraling path with higher speed, thus picking up more moisture. Thus the second effect of earth's rotation favors the poles. As a result, there are two additional attractors for convection at the poles.

The two types of attraction due to earth's rotation are depicted schematically in Fig. 1. Curve A (positive means southward) is the strength of the attraction due to the first effect with positive value denoting southward attraction; its value is zero at the equator, the center of the attractor. And curve B (positive means northward attraction) is the strength of the attraction due to the second effect of earth's rotation or due to the second term on the right hand side of Eq. (1). Being related to the thermodynamics and the circulation of the model atmosphere, curve B depends on the choice of the cumulus parameterization scheme (whereas curve A does not). Like the f^2 term, the |F| term is positive and

Corresponding Author address: Winston C. Chao, Mail Code 913, NASA/GSFC, Greenbelt, MD, 20771. Winston.chao@gsfc.nasa.gov

has a stabilizing effect. In Fig. 1 we have incorporated the effect of the |F| term in curve B to give curve B a somewhat smaller magnitude. Both curves are anti-symmetric with respect to the equator; thus only the picture in the northern hemisphere is given. Curve A is obtained by assuming that its magnitude is related to the latitudinal gradient of f^2; i.e., $\partial f^2 / \partial \phi = 8 \Omega^2 \sin\phi \cos\phi$ (where Ω is earth's rate of rotation and ϕ the latitude). It is reasonable to assume that the magnitude of curve A is large when the latitudinal gradient of f^2 is large. Another supporting argument for using the latitudinal gradient is that we can identify the location of the ITCZ as where σ^2 is a minimum, or $\partial\sigma^2 /\partial\phi = 0$, at least based on the linear theory. Thus at the location of the ITCZ $\partial f^2/\partial\phi$ is balanced by the latitudinal gradient of the second term on the right hand side of Eq. (1) (assuming |F| is absorbed in this term.), or curve A is balanced by curve B. Since we have plotted curve A only in a schematic way, we only need to assert that curve A is zero at the equator and increases first and then decreases northward and reaches zero at the north pole. This assertion is reasonable in the sense that the strength of attraction is supposed to be zero at the center of the attractor (the equator) and curve A is supposed to be zero at the north pole (an unstable equilibrium location) also due to the symmetry there. Also we need to assert that the slope of curve A at the equator is nonzero according to the above equation for $\partial f^2/\partial\phi$.

As we mentioned above, curve B (positive means northward attraction) is related to the dependence of the second term on the right hand side of Eq. (1) on the earth's rotation and is due to two attractors at the poles. In the northern hemisphere this attraction is toward the north pole, thus curve B is positive in the northern hemisphere and is zero at the north pole, the center of the attractor, and at the equator due to symmetry. In Fig. 1 we have drawn curve B in a way that can best fit the experimental results. Why the peak of curve B is in the tropical region instead of middle or high latitudes needs to be explained. A convective system in the northern hemisphere, according to the definition of curve B, experiences attraction toward the north pole and this attraction is related to the gradient of f; thus it increases toward the equator. But when close to the equator, due to the large size of the convective system, part of the convective system covers a domain south of the equator and thus experiencing the attraction from the attractor at the south pole. At the equator the attraction due to both poles cancel and curve B should be zero. Therefore curve B has a peak close to the equator.

In Fig. 1 we have plotted curve B for both RAS and MCA. B_{ras} is larger than B_{mca}, because MCA has a more stringent criterion for convection to occur (i.e., the relative humidity has to be saturated). Thus with MCA when convection does occur it is more intense and concentrated in a smaller area. Such concentration reduces the chance for convective circulation to pick up moisture at the surface. This smaller scale means that the second effect of rotation, as described in the beginning of this section is smaller due to the fact the boundary layer air, spending less time (between entering the boundary layer from the downdraft and exiting from the boundary layer in the updraft) to be affected by the Coriolis force and to pick up moisture. As a consequence the magnitude of curve B is smaller.

When a convective scheme that resembles MCA is gradually changed to one that resembles RAS, the ITCZ can switch from the equator to an off-equatorial location abruptly. This corresponds to the fact that during the rise of curve B when the slope of curve B at the equator surpasses that of curve A, the peak of curve B already exceeds curve A by a large amount. This large difference pulls the ITCZ away from the equator at a fast rate. This accounts for the sudden switch of the ITCZ location away from the equator on day 252 in Fig. 9 of CC01. The reverse switch is much slower as shown in Fig. 8 of CC01, since the difference between the two curves is much smaller.

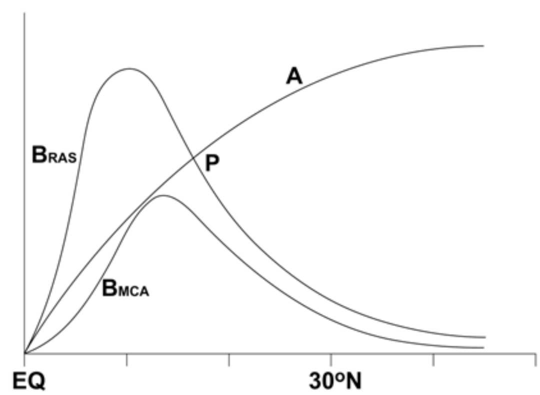

Fig. 1. Schematic diagram of the strength of the two types of attraction acting on convective systems. When RAS is used the ITCZ is located at the latitude of P and when MCA is used the ITCZ is at the equator.

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References

Chao, W. C., and B. Chen, 2001: Multiple quasi-equilibria of the ITCZ and the origin of monsoon onset. Part II. Rotational ITCZ attractors. *J. Atmos. Sci*. **58**, 2820-2831. Other references are given in the reference section of this paper.