GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L18814, doi:10.1029/2007GL030950, 2007

# Abrupt seasonal variation of the ITCZ and the Hadley circulation

Yongyun Hu,[1] Dawei Li,[1] and Jiping Liu[2]

Received 16 June 2007; revised 22 August 2007; accepted 30 August 2007; published 28 September 2007.

[1] Using Global Precipitation Climatology Project (GPCP) daily data, we show that the seasonal migration of the global zonal-mean intertropical convergence zone (ITCZ) is not smooth, but jumps from the winter hemisphere to the summer hemisphere. The abrupt migration is within 10 days. Detailed analyses reveal that the phenomenon of the abrupt seasonal migration of the ITCZ mainly exists over particular tropical domains, such as Indian Ocean, western and central Pacific, and South America, which gives the rise of the jump of the global zonal-mean ITCZ. Because the ITCZ constitutes the ascending branch of the Hadley circulation, we also examine whether there exists such an abrupt seasonal change in the Hadley circulation. It is found that the intensity of the Hadley cells evolves smoothly with time. However, the horizontal scales of the Hadley cells demonstrate abrupt seasonal changes, corresponding to the abrupt seasonal migration of the global ITCZ. The winter cell extends rapidly across the equator, while the summer cell rapidly narrows. This suggests that the solsticial cell is the dominant component of the Hadley circulation, and that the equinoctial symmetric pattern is ephemeral. **Citation:** Hu, Y., D. Li, and J. Liu (2007), Abrupt seasonal variation of the ITCZ and the Hadley circulation, *Geophys. Res. Lett.*, *34*, L18814, doi:10.1029/2007GL030950.

## 1. Introduction

[2] The intertropical convergence zone (ITCZ) is one of the most prominent features in the tropical atmosphere. Convergence of inter-hemisphere trade winds leads to strong convective cloud systems, heavy precipitation, and intense latent-heat release within the ITCZ. Because of the importance of the ITCZ to tropical and global climate and weather, the subject of the ITCZ has been frequently revisited with various interests. To our knowledge, the most systematic studies on ITCZ climatology are the works by *Waliser and Gautier* [1993] and *Mitchell and Wallace* [1992] and the references therein. One of the key points in these works is the seasonal migration of the ITCZ position. It was shown, based on monthly observational datasets, that the seasonal migration of the ITCZ location is nearly sinusoidal, following the annual cycle of surface solar heating. Here, we use Global Precipitation Climatology Project (GPCP) daily data to show that the seasonal migration of the ITCZ is not smooth. Instead, the ITCZ jumps from the winter to the summer hemisphere.

[3] Because upward air motions associated with the ITCZ constitutes the ascending branch of the Hadley circulation, it is a natural speculation that the abrupt seasonal migration of the ITCZ would be accompanied with abrupt changes in the Hadley circulation. Whether the Hadley circulation has abrupt seasonal changes is actually a controversial point in theoretical studies. *Lindzen and Hou* [1988] found in their steady axisymmetric model that the strength of the Hadley circulation is highly sensitive to the latitude of the maximum surface heating, and that a small displacement of the maximum heating source off the equator can cause a cross-equator cell which is much stronger than the equatorially symmetric cells. They thus suggested that the solsticial cell would be the dominant component of the Hadley circulation. A similar result was showed by *Fang and Tung* [1996]. However, *Fang and Tung* [1999] found that the seasonal transition of the intensity of the Hadley circulation is not as abrupt as suggested by Lindzen and Hou. *Walker and Schneider* [2005] recently argued that the abrupt transition in Lindzen and Hou's model is because of the rigid lid they used. *Dima and Wallace* [2003] analyzed reanalysis data and showed no evidence of abrupt transition of the intensity of the Hadley circulation in the real atmosphere. Here we show that the Hadley circulation indeed has abrupt seasonal changes corresponding to the abrupt seasonal migration of the ITCZ. The abrupt change is not reflected in the intensity of the Hadley circulation, but in its horizontal scales.

[4] In this paper, we will first show the abrupt seasonal migration of global and regional ITCZs using 10-year (1997–2006) GPCP daily 1° × 1° gridded precipitation data [*Huffman et al.*, 2001]. Second, we re-examine the seasonal transition of the Hadley circulation. The Hadley circulation is characterized with the mean meridional mass streamfunction, which is derived from 18-year (1979–1996) climatological-mean daily meridional winds from the National Center for Environmental Prediction/National Center for Atmospheric Research reanalysis [*Kalnay et al.*, 1996].

## 2. Seasonal Migration of the ITCZ

[5] Figure 1a shows the annual cycle of 10-year climatological-mean, global zonal-mean precipitation from daily GPCP data. The ITCZ is characterized by the heavy precipitation belt. It is obvious that there are two jumps of the rainfall belt from the winter to the summer hemisphere. One occurs around day 100. It takes about 10 days (from day 95 to 105) for the rainfall belt jumping from about 5°S to 5°N. The other one occurs around day 345 (from day 340 to 350). The timing of the first abrupt migration lags behind that of surface solar heating by about 20 days, and the timing of the second one lags behind by nearly 3 months.

---

[1] Department of Atmospheric Sciences, Peking University, Beijing, China.

[2] National Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China.

0094-8276/07/2007GL030950$05.00

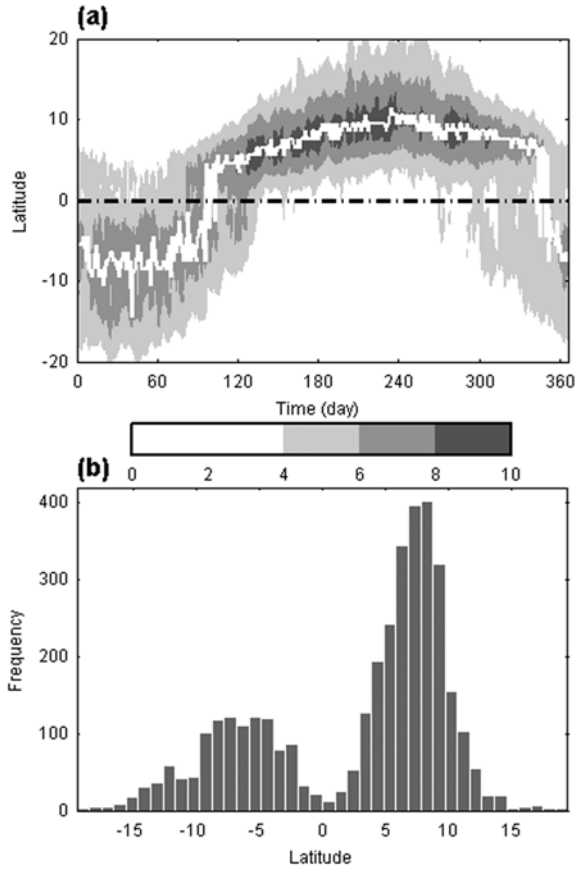

**Figure 1.** (a) Annual cycle of GPCP global zonal-mean tropical precipitation, averaged over 1997–2006. Grey-shading is for daily precipitation, and interval is 2 mm day$^{-1}$. To highlight heavy rainfall, precipitation less than 4 mm day$^{-1}$ is not shaded. Solid white line marks the maximum daily precipitation. (b) Histogram of days with maximum precipitation as a function of latitudes.

The period of the abrupt migration is so short that it can hardly be demonstrated with monthly data. *Xian and Miller* [2007] found a similar result using daily Tropical Rainfall Measuring Mission data.

[6] Figure 1b shows the histogram of days with maximum zonal-mean precipitation as a function of latitudes. It has two well separated peaks. The northern peak is located between 8°N and 9°N, with a maximum at 400 days. The southern peak is relatively weak and flat, with a maximum at about 120 days. An important reason for the asymmetry is because the ITCZ over eastern Pacific and Atlantic stays at north of the equator almost all time of year, as shown below. The trough near the equator is very pronounced, with a minimum at about 10 days. These also suggest that the ITCZ rarely stays over the equator, but jumps from one hemisphere to the other, consistent with Figure 1a.

[7] The temporal and spatial structures of the ITCZ vary largely over different tropical domains. For example, the ITCZ over eastern Pacific and Atlantic is limited into a narrow zone and does not move very much, whereas over western Pacific and Indian Ocean the narrow banded structure is washed out by strong monsoon flows and large ocean warm pools, and the ITCZ is much broader in latitude and has large seasonal variations. To demonstrate the differences in temporal and spatial structures of regional ITCZs, *Waliser and Gautier* [1993] divided the tropics into 7 longitudinal domains. Here, to show whether regional ITCZs have abrupt seasonal migration, we follow the idea by Waliser and Gautier and divide the tropics into 7 contiguous domains, whose longitude limits are specified in Table 1. Note that the longitude limits here are slightly different from those given by *Waliser and Gautier* [1993], in which the domains are not contiguous.

[8] Annual cycles of the 7 regional ITCZs are plotted in Figure 2. Over Africa, the annual cycle of the ITCZ is nearly sinusoidal. In contrast, the heavy-rainfall band over Indian Ocean jumps to the north of the equator around day 130, while a relatively weak rainfall band develops in the south of the equator. Due to the existence of the southern rainfall band, a jump from north to south is less apparent. Similar to that over Indian Ocean, the ITCZ over western Pacific also has abrupt seasonal migration. A clear jump occurs around day 130, and an arguable one is around day 320. As mentioned above, the regions of Indian Ocean and western Pacific are dominated by monsoon circulations. Thus, the seasonal transition of the rainfall bands in the two regions is largely influenced by the onset of monsoon flows. Comparison of timings between rainfall band jumps and monsoon onsets [*Li and Zeng*, 2002] suggests that the timing of rainfall band jumps over the two regions in boreal spring roughly matches that of summer monsoon onsets, and that the timing of the north-south jump over western Pacific corresponds to the timing of Australia summer monsoon onset.

[9] The case over central Pacific is different due to the existence of the well-known feature of double ITCZs in this region. One can see that there are two nearly parallel bands of precipitation straddling the equator over almost all time of year, with the dominant branch in the summer hemisphere. Therefore, there are no jumps of the ITCZ from one hemisphere to another. Instead, there are two rapid switches in precipitation intensity between the two rainfall bands. The first rapid switch occurs around day 90, and the other one occurs around day 340. The situations over eastern Pacific and Atlantic are similar. The ITCZ stays in the north of the equator for almost all time of year, with a nearly sinusoidal nature. This is because cold sea surface temperatures (SST) in the two domains, due to ocean upwelling, suppress convection [*Mitchell and Wallace*, 1992; *Philander et al.*, 1996]. Over South America, the migration of the ITCZ in the boreal spring appears to be smooth, whereas a clear jump occurs at about day 310. The abrupt migration of the ITCZ over South America from north to south was also noticed by *Horel et al.* [1989], using 5-day mean outgoing longwave radiation data. They explained that during the process from south to north, convective systems are oriented zonally (mainly over land surface of Central and South American continents), whereas for the north-south transition the orientation of convection is meridional, involving part of the oceanic surface of western Atlantic. This suggests that ITCZ migration over land surfaces is smooth (recall the case over Africa), while the ITCZs over oceanic surfaces jump across the equator.

[10] The above results reveal that the abrupt seasonal migration of the global zonal-mean ITCZ arises from the

**Table 1.** Longitude Limits for the 7 Contiguous Tropical Domains

| Domain | Longitude Limits |
|---|---|
| Africa | 0°–45°E |
| Indian | 45°E–105°E |
| West Pacific | 105°E–150°E |
| Central Pacific | 150°E–160°W |
| East Pacific | 160°W–80°W |
| South America | 80°W–45°W |
| Atlantic | 45°W–0° |

cross-equator jumps of regional ITCZs over particular domains. Specifically, the abrupt migration in boreal spring is due to contributions from Indian Ocean, western and central Pacific, and the abrupt migration in early December arises from western and central Pacific and South America.

## 3. Seasonal Transition of the Hadley Circulation

[11] To verify how the Hadley circulation responds to the abrupt seasonal migration of the global ITCZ, we take two approaches. The first one is to repeat the analysis of empirical orthogonal functions (EOF) for mean meridional mass streamfunctions by *Dima and Wallace* [2003] using daily NCEP/NCAR reanalysis data, instead of using monthly data. This is to test whether a possible abrupt transition of the intensity of the Hadley circulation was smoothed out in monthly data. The second is to examine how horizontal scales of the Hadley cells vary with time.

[12] Figure 3a shows the spatial pattern of the leading EOF mode of the mean meridional mass streamfunction. Similar to that given by *Dima and Wallace* [2003], this leading mode accounts for 97.09% of the variance of the climatological-mean mass streamfunction. The time evolution of the leading principal component is plotted in Figure 3b. It is obvious that this seasonally reversing solsticial mode has no abrupt changes in both spring and fall, but varies nearly linearly. This suggests that the strength of the Hadley circulation has no abrupt transition in daily data, consistent with the result derived from monthly data.

[13] In contrast to the nearly linear transition of the strength of the Hadley circulation, horizontal scales of the Hadley cells demonstrate abrupt changes. Figure 4a shows the annual cycle of the half width (the distance from each cell center to the separation line between the two cells) of the Hadley cells at 300 hPa. One can readily find two abrupt changes: around day 110 and 331, respectively. The abrupt changes are within 10 days. Note that the timing of the abrupt changes in horizontal scales does not exactly match that of the global ITCZ. The abrupt change in boreal spring occurs about 10 days later than that of the global ITCZ, and the one in boreal winter is about 15 days earlier. Why there exists such a mismatch is currently under research.

[14] The abrupt changes in horizontal scales are very large. During the abrupt change in boreal spring (day 108–115), the half-width of the southern cell rapidly extends from about 11 degree to 17 degree latitudes, widened by about 55%. At the same time, the half-width of the northern cell shrinks from about 16 degree to 9 degree latitudes, narrowed by about 44%. During the second abrupt change (day 327–337), the northern cell is widened by about 11 degree latitudes (90%). The southern cell is narrowed

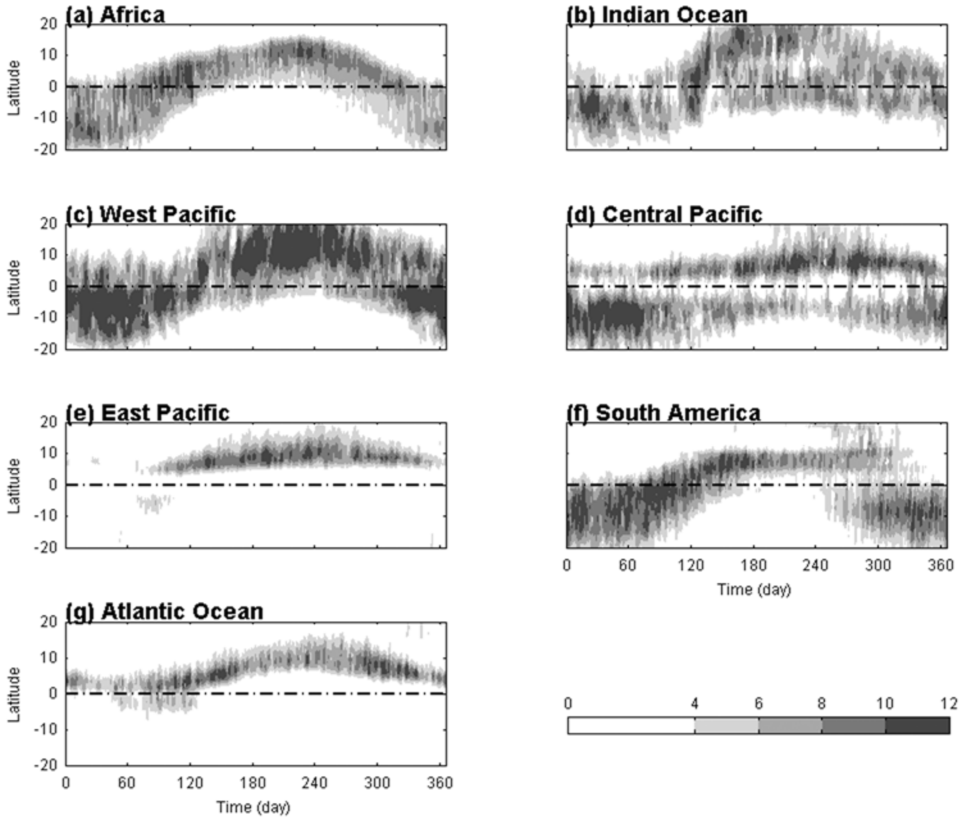

**Figure 2.** Same as for Figure 1a, except for the 7 regions specified in Table 1.

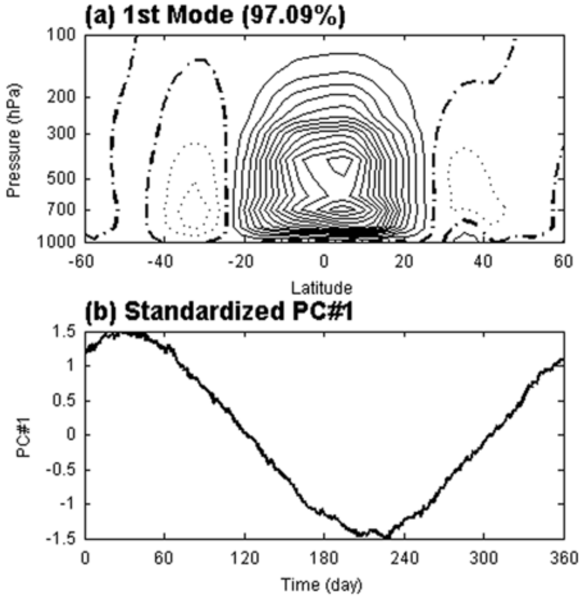

**Figure 3.** (a) The leading EOF mode of the climatological-mean daily mass streamfunction. Contour interval is $1 \times 10^{10}$ kg s$^{-1}$. (b) Annual cycle of anomalies of the principal component normalized by the standard deviation.

by about 9 degree latitudes (44%). The narrowing of the summer cell is roughly compensated by the widening of the winter cell.

[15] The abrupt changes in horizontal scale of the Hadley cells can be interpreted by compositing of the annual mean and the seasonally reversing leading EOF mode. Since the leading mode accounts for 97.09% of the variance of the climatological-mean mass streamfunction about the annual mean, all higher-order modes are less important. For the annual mean Hadley circulation, the separation line between the two cells is located near the equator. During the boreal winter, the streamfunctions of the leading EOF mode and the annual mean northern cell have the same sign. Composition of the two yields a separation line located in the south of the equator. As the leading EOF mode reverses its sign during seasonal transition from boreal winter to summer, composition of the two leads to a separation line in the north of the equator, suggesting a rapid transition. It is the same for seasonal transition from austral winter to summer.

[16] It is important to point out that the abrupt seasonal changes in horizontal scales of the Hadley circulation mainly exist at levels above 500 hPa. At lower levels, seasonal changes become smooth. This can be found out by comparing Figures 4b and 4c. Before the transition, the upper part of the separation line is in the north of the equator. At 300 hPa, the separation line is at about 4°N. 10 days later, it moves to about 7°S. The lower part of the separation line also show southward movement. However, the movement is small. Similar situation can be found for the case in the boreal spring.

## 4. Discussion and Conclusions

[17] Using daily GPCP daily precipitation data, we have shown that the global zonal-mean ITCZ has abrupt seasonal migration from the winter to the summer hemisphere. The process of the abrupt migration is within 10 days. Detailed analyses show that the abrupt migration in the boreal spring mainly arises from cross-equator jumps of regional ITCZs over oceanic domains such as Indian Ocean, western and central Pacific, and that the second one is due to contributions from western and central Pacific and South America. Regional ITCZs over Africa, eastern Pacific and Atlantic domains do not show abrupt migration.

[18] An important question is what causes the abrupt seasonal migration of the ITCZ. In-depth discussion on this problem is beyond the scope of the present short paper. Here, we just present some brief discussion. The spatial distribution of tropical SSTs plays an important role in the abrupt migration of the ITCZ. For example, in central Pacific SSTs at the equator are usually cooler than that away from the equator on both sides due to equatorial ocean upwelling. Because convection favors warmer SSTs, the ITCZ does not stay at the equator but jumps from one hemisphere to the other. The close relationship between the ITCZ location and off-equator warm SSTs was pointed out by *Bjerknes et al.* [1969]. However, in the Indian Ocean and western Pacific warm-pool regions where maximum SST is at the equator, the ITCZ still prefers latitudes off the equator. Monsoon circulations play an important role in the abrupt seasonal migration of the ITCZ in the two regions. The timing of the abrupt migration of the ITCZ is consistent with the timing of monsoon onset. *Waliser and Somerville* [1994] suggested that the off-equator preference of the ITCZ in these regions is related to a positive feedback between middle tropospheric latent heating associated with moist deep convection and boundary-layer convergence of moisture, which tends to enhance convection at latitudes off the equator. Different mechanisms for the off-equator preference of the ITCZ have also been proposed. The reader is referred to *Charney* [1971] and *Holton* [1974]. Though these works are not directly related to seasonal migration of the ITCZ, they all have the implication that the ITCZ would skip over the equator during its seasonal migration. In a recent work, *Xian and Miller* [2007] used an idealized model and found that the thermal inertia of underlying ground plays an important role in ITCZ seasonal migration. They showed that a weak ground thermal inertia leads to smooth seasonal migration of the ITCZ, while a larger thermal inertia (not very large) causes abrupt migration. Their results help explain the different behavior of seasonal migration of regional ITCZs between land and oceanic surfaces, i.e., smooth over land and jumping over oceans.

[19] Though the strength of the Hadley circulation has smooth seasonal transition, the horizontal scales of the Hadley cells have abrupt seasonal changes at levels above 500 hPa in corresponding to the abrupt seasonal migration of the global ITCZ. The rapid widening of the winter cell roughly equals the abrupt narrowing of the summer cell. The rapid changes in the half-width of the Hadley cells are rather large, ranging from 44% to 90%. From the point of view of horizontal scales, the solsticial cell is indeed the dominant component of the Hadley circulation, while the equatorially symmetric equinoctial pattern is ephemeral. Why the abrupt change in horizontal scales only exists at levels above 500 hPa is currently under research and will be presented in future works.

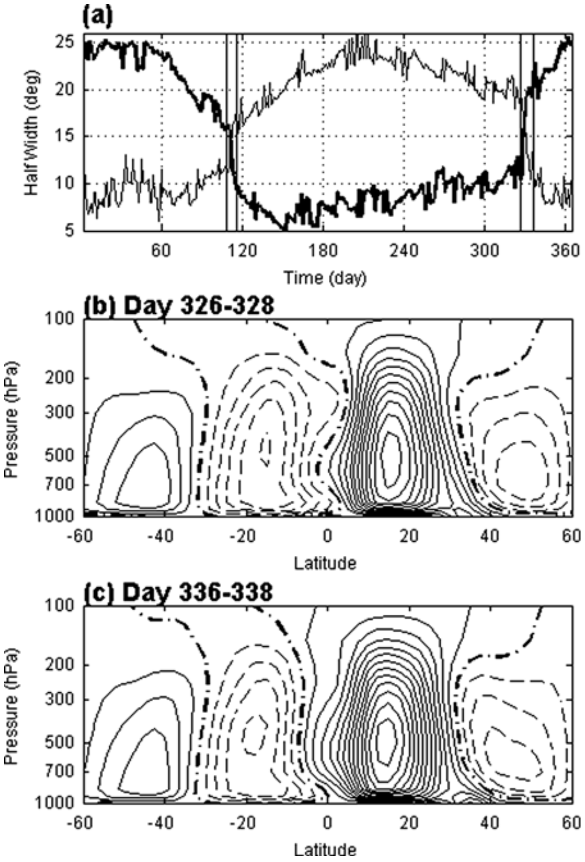

**Figure 4.** (a) Annual cycle of the half-width of the Hadley cells at 300 hPa. The thick line is for the northern cell, and the thin line is for the southern cell. Each abrupt change is marked by two vertical lines. The four vertical lines correspond to day 108, 115, 327 and 337, respectively. (b, c) Mass streamfunctions averaged over days 326–328 and days 336–338, respectively. Solid line, clockwise rotation; dashed-line, anticlockwise rotation; thick dash-dotted line, streamfunction lines with values of 0 kg $s^{-1}$.

[20] **Acknowledgments.** We are grateful to P. Xian and R. L. Miller for showing us their unpublished manuscript and to K. K. Tung for suggestions on an early draft. We also thank two anonymous reviewers for their very helpful comments. Y. Hu and D. Li are supported by the Ministry of Education of China (106002), by the NSF of China (40575031 and 40533016), and by the National Basic Research Program of China (973 Program, 2007CB411801). J. Liu is supported by the National Basic Research Program of China (2006CB403605).

## References

Bjerknes, J. R., L. J. Allison, E. R. Keins, F. A. Godshall, and G. Warnecke (1969), Satellite mapping of the Pacific tropical cloudiness, *Bull. Am. Meteorol. Soc.*, *50*, 313–322.

Charney, J. G. (1971), Tropical cyclogenesis and the formation of the Intertropical Convergence Zone, in *Mathematical Problems of Geophysical Fluid Dynamics*, *Lectures Appl. Math.*, vol. 13, edited by W. H. Reid, pp. 355–368, Am. Math. Soc., Providence, R. I.

Dima, I. M., and J. M. Wallace (2003), On the seasonality of the Hadley cell, *J. Atmos. Sci.*, *60*, 1522–1527.

Fang, M., and K. K. Tung (1996), A simple model of nonlinear Hadley circulation with an ITCZ: Analytic and numerical solutions, *J. Atmos. Sci.*, *53*, 1241–1261.

Fang, M., and K. K. Tung (1999), Time-dependent nonlinear Hadley circulation, *J. Atmos. Sci.*, *56*, 1797–1807.

Holton, J. R. (1974), Comments on "Movable CISK," *J. Atmos. Sci.*, *43*, 606–630.

Horel, J. D., A. N. Hahmann, and J. E. Geisler (1989), An investigation of the annual cycle of convective activity over the tropical Americas, *J. Clim.*, *2*, 1388–1403.

Huffman, G. J., R. F. Adler, M. Morrissey, D. T. Bolvin, S. Curtis, R. Joyce, B. McGavock, and J. Susskind (2001), Global precipitation at one-degree daily resolution from multi-satellite observations, *J. Hydrometeorol.*, *2*, 36–50.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–471.

Li, J., and Q. Zeng (2002), A unified monsoon index, *Geophys. Res. Lett.*, *29*(8), 1274, doi:10.1029/2001GL013874.

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

Mitchell, T. P., and J. M. Wallace (1992), On the annual cycle in equatorial convection and sea surface temperature, *J. Clim.*, *5*, 1140–1156.

Philander, S. G. H., et al. (1996), Why the ITCZ is mostly north of the equator?, *J. Clim.*, *9*, 2958–2972.

Waliser, D. E., and C. Gautier (1993), A satellite-derived climatology of the ITCZ, *J. Clim.*, *6*, 2162–2174.

Waliser, D. E., and R. C. J. Somerville (1994), Preferred latitudes of the intertropical convergence zone, *J. Atmos. Sci.*, *51*, 1619–1639.

Walker, C. C., and T. Schneider (2005), Response of idealized Hadley circulations to seasonally varying heating, *Geophys. Res. Lett.*, *32*, L06813, doi:10.1029/2004GL022304.

Xian, P., and R. L. Miller (2007), Abrupt seasonal migration of the ITCZ into the summer hemisphere, *J. Atmos. Sci*, in press.

---

Y. Hu and D. Li, Department of Atmospheric Sciences, Peking University, Beijing 100871, China. (yyhu@pku.edu.cn)

J. Liu, National Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China.