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Atmospheric Chemistry and Physics Discussions

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Interactive Comment

Interactive comment on "Observed poleward expansion of the Hadley circulation since 1979" *by* Y. Hu and Q. Fu

Y. Hu and Q. Fu

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Reply to general comments:

First, we thank the reviewer for very helpful reviews.

Second, we agree that it is a weak part in our paper that we have not provided in-depth discussion on possible mechanisms for the broadening of the Hadley circulation, and that it is important to improve this part. The following is some qualitative discussion, based on Held and Hou's (1980) theoretical arguments, on factors which influence the width of the Hadley circulation. The discussion here will be modified and added to the revised version.

Under assumptions of angular momentum conservation and thermal wind balance, the latitude of the poleward edge, ϕ_H, of the Hadley circulation is determined by

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$$\phi_H \approx \left(\frac{5gH\Delta\theta}{3\Omega^2 a^2 \theta_0}\right)^{\frac{1}{2}},$$

where H is the tropical tropopause height, θ_0 is the global mean radiative equilibrium potential temperature, $\Delta\theta$ is the pole-equator potential temperature difference, and g, Ω and a indicate earth's gravity, angular speed of rotation, and radius, respectively. For the case of greenhouse-induced global warming, θ_0 becomes larger, and $\Delta\theta$ becomes smaller because temperatures at high latitudes have much larger increases than in the tropics. Both changes would lead to a narrower Hadley circulation under the assumptions in Held and Hou (1980). However, the above formula was obtained in the case without taking the effect of extratropical waves into account. In the presence of extratropical eddies, angular momentum conservation will break down at the edges of the Hadley circulation. Thus, the activity of extratropical waves has important influences on the extension of the Hadley circulation, as pointed out by Held (Woods Hole GFD Lecture Notes, 2000). Consider that changes in horizontal temperature gradients must cause changes of extratropical baroclinic wave activity. A smaller $\Delta\theta$ would generate weaker baroclinic wave activity in the extratropics, which allows angular momentum conservation extending further poleward (Held, 2000). Thus, the Hadley circulation will become broader. On the other hand, increasing greenhouse gases will also cause tropical SST warming, which leads to a larger H and thus a broader Hadley circulation. Lu et al. (2007, which is referred in our paper) analyzed results from the AR4 simulations with 21st century increasing greenhouse gas scenarios and found that the poleward expansion of the Hadley circulation in these simulations has no close correlations with variations in the tropical tropopause height, but has statistically significant positive correlation with a weakening of baroclinic instability in the extratropics. Therefore, they argued that the poleward expansion of the Hadley circulation in the AR4 simulations is caused due to the weakening of baroclinic wave activity in the extratropics. Since the expansion magnitudes of the Hadley circulation in AR4 simulations is much weaker than ours (less than 1 degree latitude over 100 years vs. 2-4.5 degrees latitude over 27 years), it is not clear whether there is a resemblance between what found by Lu et al. from the AR4 simulations and the expansion of the Hadley circulation in the reanalyses. It is also possible that current GCMs have the lack of capability in simulating the observed expansion of the Hadley circulation.

As pointed out in the reply to referee 2, we are concerned with whether current coupling GCMs can properly simulate tropical SST warming in responding to increasing greenhouse gases. To test how the Hadley circulation responds to the observed tropical SST warming in recent decades, we are carrying out GCM simulations with forcing of observed time-varying SST. Results will be presented in future studies if they are interesting. In addition, we will also analyze simulation results from the Atmospheric Model Intercomparison Project (AMIP), which was designed to simulate atmosphere's responses to the observed sequence of monthly averaged global sea surface temperatures and sea-ice distributions, to study how the width of the Hadley circulation responds to SST changes.

"How does the poleward expansion of the Hadley Cell relate to variations in its intensity, if at all?" To our knowledge, there are no theoretical works on this issue. For ERA40 and NCEP/NCAR reanalyses, the expansion of the Hadley circulation mainly occurs in summer and fall seasons for each hemisphere, while the intensification of the Hadley circulation mainly occurs in winter and spring seasons. NCEP/DOE reanalysis also shows expansion of the Hadley circulation in summer and fall seasons, but no significant intensification in any seasons. It appears that the two do not happen at the same time. Lu et al. (2007) found that the expansion of the Hadley circulation is accompanied with a weakening of intensity in AR4 simulations. For paleoclimate simulations, results are not consistent. For example, Pierrehumbert (2005, JGR) found a very narrow (descending at about 20žN (S)) and strong Hadley circulation over a hard snowball earth, whereas Williams and Bryan (2006, JCLIM) found a weakening and equatorward shrinking of the Hadley circulation.

"ĚZhang et al. (Nature, 448, 461-465, 2007)?". Thanks for pointing out this paper. In the revised version, the paper will be refereed in addressing that current GCMs may not have the capability in simulating changes in the Hadley circulation. Using Global

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Precipitation Climatology Project (GPCP) data, we found that subtropical precipitation in the Southern Hemisphere also has significant decrease since 1979, in addition to that in the Northern Hemisphere.

Reply to Specific and technical comments:

Pg 9368, ln 11: Change will be made.

Pg 9368, ln 26: Change will be made.

Pg 9370, ln 5: The NCEP/DOE reanalysis is an updated version of the NCEP/NCAR reanalysis by eliminating several errors. Corrections to these errors are very specifically pointed out in Kanamitsu et al. (2005). We feel that it may not be good to repeat what the authors have said.

Pg 9371, ln 2 and elsewhere: Changes will be made.

Pg 9371, ln 20: Changes will be made in the revised version. One sentence will be added, that is, "Because reanalyses before 1979 are less reliable because of not including satellite observations, trend analyses before 1979 are not shown."

Pg 9372, ln 24: We agree that NCEP/NCAR and NCEP/DOE reanalyses also have problems. However, Trenberth and Smith (2006) particularly pointed out that ERA40 reanalysis yields less reliable tropical trends due to bias adjustment in assimilating satellite data. By referring their paper, we tend to say that the much larger expansion of the Hadley circulation in ERA40 is possibly due to lower reliability of the data. Held also pointed out that ERA40 has a very unrealistically large positive trend in tropical precipitation (personal communication).

Pg 9372, ln 25-26: The ERA40 data used here is from 1979-2002 (24 years). The annual mean expansion of the Hadley circulation over the 24 years is about 2.6 degrees latitude. If it is linearly extrapolated to 2005 (for comparing with the 27-year (1979-2005) trend from NCEP/NCAR and NCEP/DOE), the expansion becomes about 2.9 degrees latitude.

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Pg 9373, ln 4: Change will be made.

Pg 9373, ln 9-10: Thanks for pointing out this. The sentence will be changed to "For the OLR records the locations of the poleward edges of the Hadley circulation are roughly defined as the most poleward latitude at which the zonal mean OLR is equal to 250 Wm-2."

Pg 9373, ln 22-23: Change will be made.

Pg 9375, ln 15-17: This sentence will be removed. The statement was made based on the simulation results by Polvani and Kushner (2002, Tropospheric response to stratospheric perturbations in a relatively simple general circulation model. GRL, 29, 18-1-18-4). They showed that sufficiently strong stratospheric polar cooling can cause a strengthening and poleward shift of the winter-hemisphere subtropical tropospheric jet. In the reanalyses, however, the Hadley circulation does not show expansion in spring when stratospheric polar cooling due to ozone depletion occurs. The perturbation of stratospheric polar cooling used by Polvani and Kushner seems to be much stronger than that induced by ozone depletion in spring. Now, we feel that it would be better not to make such a statement if there is no observational evidence.

Interactive comment on Atmos. Chem. Phys. Discuss., 7, 9367, 2007.