DECADAL CHANGES IN THE HADLEY CIRCULATION [*]

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The Hadley circulation is one of the most important atmospheric circulations. The main goal of this paper is to investigate whether the Hadley circulation has changed in the past few decades as an integral part of global climate change. We focus on two key points: one is the horizontal scale of the Hadley circulation, and the other one is its strength. Using three meteorological reanalyses, we show that the Hadley circulation has a significant expansion of about 2 to 4.5 degrees of latitude in autumn for both hemispheres since 1979, and that two of the three reanalysis datasets show strengthening of the Hadley circulation in Northern-Hemisphere winter. Trends derived from general circulation model simulations are compared with observed changes in the Hadley circulation. It is found that most simulations show poleward expansion of the Hadley circulation, with weaker magnitudes. However, most simulations display weakening of the Hadley circulation, rather than strengthening

1.Introduction

The Hadley circulation is one of the most important atmospheric circulations. It is a thermally driven meridional circulation, with warmer air rising in the tropics due to the release of latent heat and colder air sinking in the subtropics, generating an enclosed circulation in each hemisphere (Held and Hou, 1980). The Hadley circulation is fundamentally important to the global climate system. It does not only transport heat from the tropics to the subtropics and to high latitudes through extratropical eddies but also transports momentum flux to the subtropics (Lindzen, 1994). Both heat and momentum transports have important influences on subtropical jet streams, which consequently impact on waves and atmospheric circulations at middle and high latitudes. Therefore, changes in the Hadley circulation have important impacts on global climate (Diaz and Bradley, 2004).

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In the past few years, there have been growing interests in decadal changes in the Hadley circulation. These studies were concerned with two key problems: one is multi-decadal changes in intensity of the Hadley circulation, and the other one is its horizontal scales or width. Using outgoing longwave radiation (OLR) datasets from the Earth Radiation Budget Experiment (ERBE), Chen et al. (2002) and Wielicki, et al. (2002) suggested that the Hadley circulation was intensified in the 1990s. Using reanalysis datasets, Quan et al. (2002), Hu et al. (2005) and Mitas and Clement (2005) showed that the winter cell of the Hadley circulation has large intensification in the past few decades. However, whether the intensification of the Hadley cell as suggested by some of these studies is real remains controversial (Trenberth, 2002; Held and Soden, 2006).

On the other hand, results from several recent studies suggest that the Hadley circulation has poleward expansion since 1979. Using microwave sounding unit (MSU) data, Fu et al. (2006) showed an enhanced warming in the mid-latitude troposphere. Such a change in tropospheric temperatures indicates a poleward shift in the maximum horizontal temperature gradient and thus implies a poleward shift of subtropical jet streams. Since the location of the subtropical jet stream marks the poleward edge of the Hadley circulation, Fu et al. (2006) suggest a broadening of the tropics. Using total ozone data, Hudson et al. (2006) showed that the subtropical upper tropospheric front in the Northern Hemisphere shifted poleward by about 2.75 degree latitudes over 1979-2003, which also implies a poleward shift of the tropospheric subtropical jet stream. Based on mass streamfunction calculations and OLR data analyses, Hu and Fu (2007) provided direct evidence that the Hadley circulation has expended poleward since 1979. Through an analysis of tropopause heights in the subtropics using radiosonde measurements and reanalysis data, Seidel and Randel (2007) found an expansion of the tropical belt for about 4.25 degree latitudes during 1979-2005.

Changes of the Hadley circulation in both width and strength have important implications for global climate changes, especially for subtropical regions where the Hadley circulation descends. A stronger Hadley circulation would leads to stronger downward motions in the subtropics, which consequently causes less precipitation in the subtropics. A broadening Hadley circulation would leads to poleward expansion of the subtropical dry zone in both hemispheres.

In this study, our main goal is to investigate whether the changes in the Hadley circulation are responses to global climate change due to increasing greenhouse gases. To investigate the problem, we compare the trends from reanalyses with that from general circulation model (GCM) simulations. We first use three meteorological reanalysis datasets to show changes in both the width and strength of the Hadley circulation in the recent three decades. Then, we examine changes in both width and intensity of the Hadley circulation in two kinds of GCM simulations: atmospheric GCM (AGCM) simulations forced by observed sea surface temperatures (SST) and coupled atmospheric and oceanic GCM (AOGCM) simulations forced by increasing greenhouse gases. Data and methods used in this study are described in section 2. Results from reanalysis datasets are in section 3. Results from GCM simulations are presented in section 4. Discussion and conclusions are in Section 5.

2. Data and methods

The Hadley circulation is characterized with the mean meridional mass streamfunction (MMS). MMS is calculated by vertically integrating monthly meridional winds in the conventional way (Holton, 1994). Clockwise circulation (the northern cell) is defined as positive, and anti-clockwise circulation (the southern cell) is defined as negative. The locations of poleward edges of the Hadley circulation are identified as the latitudes where MMS equals 0 kg s^{-1}, which are obtained using linear interpolation. Poleward expansion of the Hadley cells is estimated by calculating linear trends of the edge latitudes. The three reanalysis datasets used in this study are from the National Center for Environmental Prediction/National Center for Atmospheric Research (Kalnay, et al., 1996), the National Center for Environmental Prediction/Department of Energy (Kanamitsu, et al., 2002) and the European Centre for Medium-Range Weather Forecasts (Uppala, et al., 2005). For simplicity, they are denoted by NCEP/NCAR, NCEP/DOE, and ERA40, respectively. The ERA40 reanalysis used here is from January 1979 to August 2002 (24 years), and NCEP/NCAR and NCEP/DOE reanalyses are from January 1979 to December 2007 (29 years).

The two kinds of GCM simulation datasets are from the Atmospheric Model Intercomparison Project (AMIP) (Gates et al., 1999) and the AOGCM simulations of the 20th century for the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) (Solomon et al., 2007). As pointed out by Gates et al. (1999), AMIP was designed to simulate the atmosphere’s evolution subject to the observed sequence of monthly averaged global sea surface temperature and sea-ice distributions from 1979 to 2000. Therefore, in AMIP simulations atmospheric compositions and the solar constant are fixed, while the AGCMs are forced by observed time-varying SST. AMIP includes 12 models: GISS_ER, IAP_FGOALS, IPSL_CM4, MIROC32_MEDRES, MPI_ECHAM5, CNRM-CM3, GFDL-CM21,

MIROC32-HIRES, MRI-CGCM23-2A, NCAR-CCSM30, NCAR-PCM1, and UKMO-HADGEM1. The first 5 models have ensemble members of simulations, and the other 7 models have only single runs. To compare with these ensemble simulations, results from the 7 single runs are averaged and presented as ensemble numbers. For IPCC-AR4 simulations, we choose 10 of 23 model results, and all the 10 models have ensemble simulations. The models are: MPI-ECHAM5, UKMO-HADCM3, NCAR, GISS-EH, GISS-ER, GFDL-CM20, GFDL-CM21, NCAR-CCSM30, UKMO-HADGEM1, GISS-AOM. Though all simulation results are available from 1979, these simulations end at different years such as 1999 or 2000. For comparison, trends from all simulations are converted into trends over 20 years.

It is noticed that the poleward expansion in all the three reanalyses mainly occurs in their summer and autumn seasons for both hemispheres. In winter and spring seasons, poleward expansions are either very weak or slightly negative, as pointed out by Hu and Fu (2007). Therefore, our analysis focuses on autumn.

3. Results from reanalysis data

3.1 Poleward expansion of the Hadley circulation

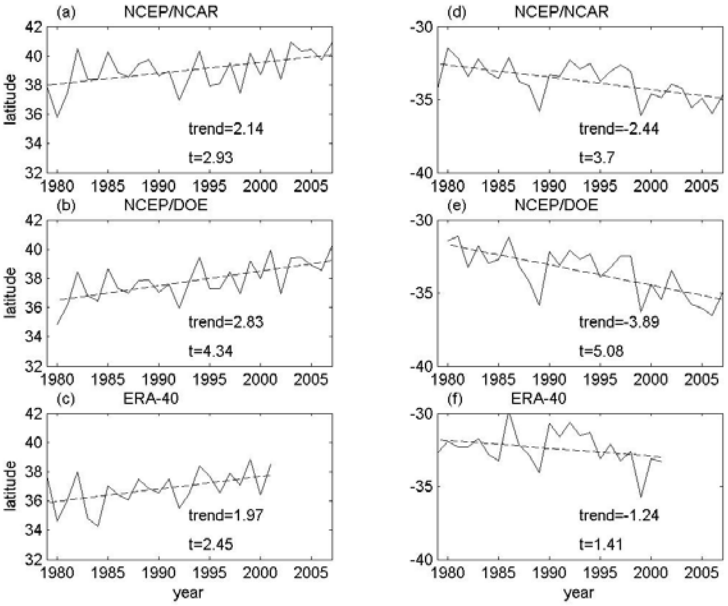

Figure 1. Time series of poleward-edge latitudes of the Hadley circulation at 500 hPa. Plots on the left panel are for NH autumn (SON), derived from three reanalysis datasets. Plots on the right panel are for SH autumn (MAM). From top to bottom, the plots are for NCEP/NCAR, NCEP/DOE, and ERA40, respectively. Trends marked in the plots are the values for the years over which reanalysis

data are available. Student t-test values are also marked in these plots. 1.7 approximately corresponds to the 90% confidence level

Figure 1 shows the time series of poleward-edge latitudes of the Hadley circulation at the 500 hPa pressure surface in both boreal and austral autumn, derived from the three reanalyses. For the left panel (Figures 1a, b, and c), all the three datasets show that the poleward edge of the northern Hadley-circulation branch exhibits a systematic poleward expansion in September-October-November (SON) from 1979 onward. For NCEP/NCAR, the linear trend in poleward-edge latitudes is about 2.14° in latitude from 1979 to 2007, with a statistical significance above the 99% confidence level (student t-test value is 2.93). For NCEP/DOE and ERA40, the poleward expansions are 2.83° and 2.40° of latitude over 1980-2007 and 1979-2001, respectively, with statistical significance all above the 98% confidence level. From Figure 1, we can find that the poleward expansion of the northern Hadley circulation branch appears to be a systematic robust feature of the analyses, but not to be caused due to the Southern Oscillation/El Nino events (e.g., 1988, 1998, and so on). In addition, the significant poleward expansion is not limited over the period since 1979. It is also found in ERA40 and NCEP/NCAR reanalyses since the 1950s. Because reanalyses before 1979 are less reliable due to not including satellite observations, trends before 1979 are not shown.

Poleward expansion is also found for the southern Hadley-circulation branch. The three plots on the right panel (Figures 1d, e, f) show time series of poleward-edge latitudes of the southern Hadley-circulation branch at 500 hPa for March-April-May (MAM). Similar to that of the northern branch, the poleward edges of the southern branch in all the three datasets demonstrate systematic southward expansions. The largest southward expansion is found in NCEP/DOE, with magnitude close to 3.89 degree latitudes over the 29 years. All the trends are statistically significant.

3.2 Intensification of the Hadley circulation

In studying the decadal changes in the strength of the Hadley circulation, Mitas and Clement (2005) examined the maximum value of MMS. Here, we show height-latitude cross-sections of trends in MMS, which better demonstrate the spatial structures of changes in the Hadley circulation. Since the intensification of the Hadley circulation mainly exists in the branch of the winter hemisphere (Mitas and Clement, 2005), our analysis also focuses on the winter season for both hemispheres. Figures 2a, b, c show the trends in MMS for Northern-Hemisphere winter, derived from three reanalyses. Three plots display different spatial structures of trends in the tropics. For NCEP/NCAR, trends in the northern tropics are positive, except for relatively weak negative trends at the lowest layers. Maximum trends more than 2.5×10^{10} kg s^{-1} over 1979-2007 are located around 300 hPa. Because the streamfunction of the northern cell is defined positive, the positive trends indicate intensification of the northern branch. Comparison with the climatological maximum value of about 16×10^{10} kgs^{-1} for the northern branch in winter, the increase of the northern-branch strength is more than 15%. For NCEP/DOE, weak positive trends are found between 10° N and 30° N, however, strong negative trends are around the equator. Thus, it is difficult to determine whether the Hadley circulation is intensified or not. For ERA40, the northern tropics are dominated by positive trends, except for the top layers in the tropical troposphere. Comparison with the climatological maximum value of about 21×10^{10} kgs^{-1}, the net increase is about 29%.

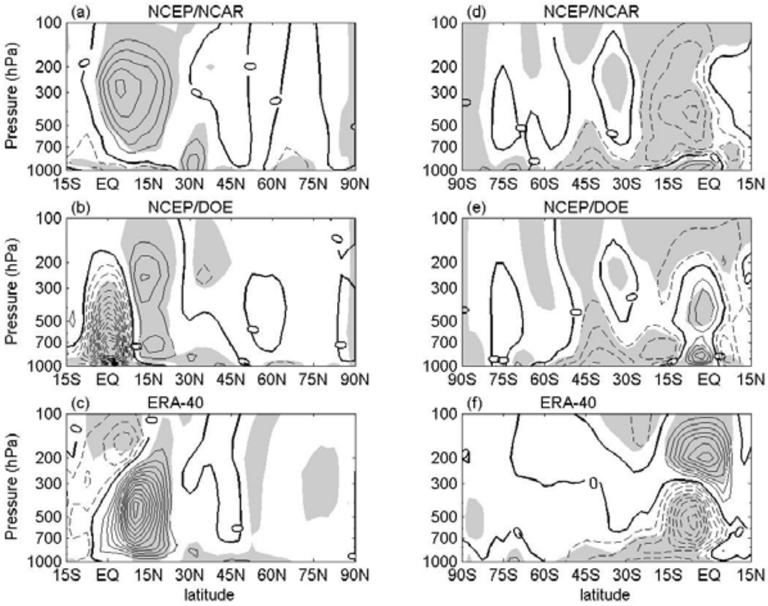

Figure 2. Trends in zonal-mean mass streamfunction. Plots on the left are for NH winter (DJF), derived from three reanalysis datasets. Plots on the right are for SH winter (JJA). From top to bottom, the plots are for NCEP/NCAR, NCEP/DOE, and ERA40, respectively. Contour interval is 0.5×10^{10} kg s^{-1} per 29, 28, and 23 years, for NCEP/NCAR, NCEP/DOE, and ERA40, respectively. Shading areas are the regions where statistical significance is above the 90% confidence level.

Plots on the right panel show trends in MMS for austral winter. For NCEP/NCAR, the southern tropics are dominated by weak negative trends. Since the southern branch is defined negative, the negative trends are indicative of intensification of the southern branch. Compared with that of the northern branch, the trends for the southern branch are much weaker. For NCEP/DOE, weak positive trends are found between the equator and 15° S, suggesting a weakening of the southern branch. For ERA40, the upper tropical troposphere shows positive trends, while the lower tropical troposphere shows negative trends, suggesting that neither the maximum value of MMS nor the whole southern branch has significant changes.

4. Simulation results

The radiative effect of increasing greenhouse gases causes warming for both SST and the troposphere (Solomon et al., 2007). If the above decadal trends in the Hadley circulation are responses to global greenhouse warming, both SST and tropospheric warming would have contributions. The AMIP simulations provide a test bed to examine how the Hadley circulation responds to SST warming. The IPCC-AR4 AOGCM simulations include warming in both the troposphere and SST forced by increasing greenhouse gases. Here, we first analyze AGCM simulations. Then, we analyze the AOGCM simulations.

4.1 Results from AMIP simulations

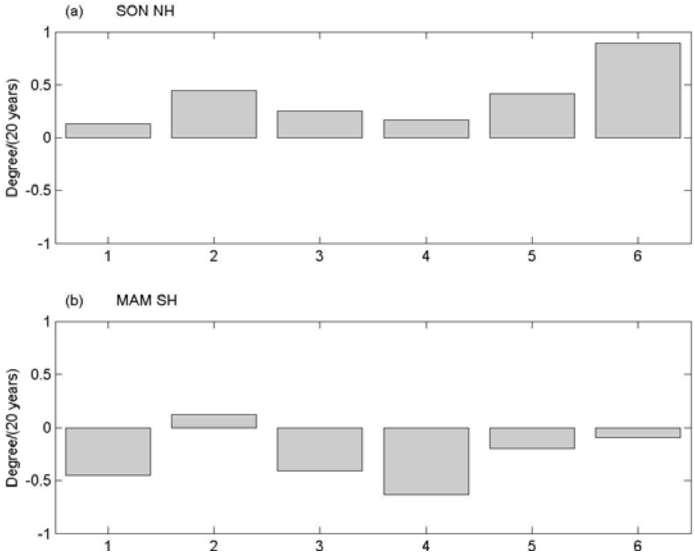

Figure 3. Poleward expansion of poleward-edge latitudes of the Hadley circulation derived from AMIP simulations. In Figure 3a, positive (negative) trends indicate poleward (equatorward) shifts of the northern branch. In Figure 3b, positive (negative) values indicate equatorward (poleward) shifts of the poleward edge of the southern branch. The bars from left to right represent trends derived from GISS_ER, IAP_FGOALS, IPSL_CM4, MIROC32_MEDRES, and MPI_ECHAM5 ensemble simulations. The last bar represents the trend in averaged simulations from 7 single model runs.

AMIP simulations also demonstrate that poleward expansion of the Hadley circulation occurs in the autumn season for both hemispheres. Figure 3a shows trends in poleward-edge latitudes of the northern branch in SON. All ensemble simulations and the averaged results from 7 single runs show poleward expansion. Magnitude varies from 0.2° to 1.0° of latitude, with an average value of about 0.5° in latitude per 20 years. For the southern branch in austral autumn (MAM, Figure 3b), the simulations also show poleward expansion, except for IAP_FGOALS. The averaged magnitude of poleward expansion is close to 0.4° in latitude over 1979-2000. The trends are statistically significant. Therefore, the results from AMIP simulations are consistent with the results in reanalyses, except for that the trends are much weaker than that from reanalyses.

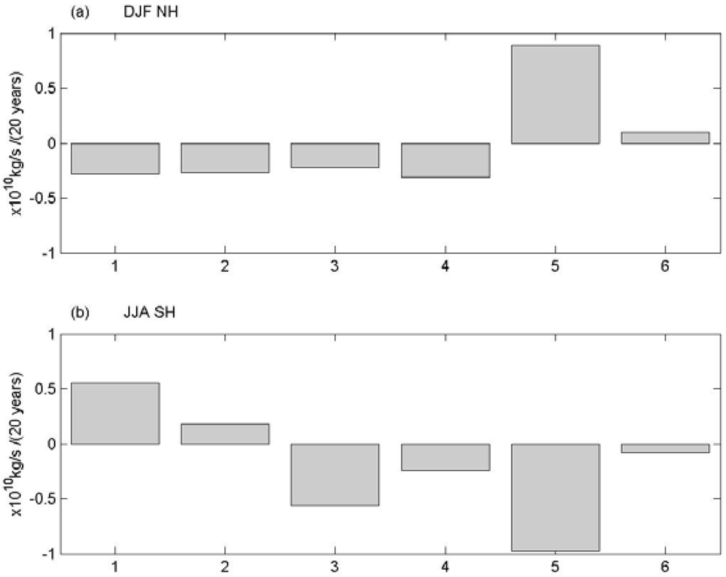

Figure 4. Trends in the maximum zonal-mean mass streamfunction, derived from AMIP simulations. The bars are in the same order as that in Figure 3. For both northern and southern branches, positive values indicate strengthening of the Hadley circulation, and negative values indicate weakening.

Figure 4a shows trends in the maximum MMS of the northern Hadley-circulation branch in boreal winter. 4 of the 5 models with ensemble simulations show weakening of the northern branch, and the averaged result from 7 single runs shows very weak strengthening. Note that these trends for either weakening or strengthening are statistically insignificant. For the southern branch in austral winter, 2 models of ensemble simulations show strengthening, whereas 3 others and the averaged result show weakening. Overall, AMIP simulations demonstrate weak weakening of the Hadley circulation, which does not support the result of intensification of the Hadley circulation in reanalyses.

4.2 Results from IPCC-AR4 simulations

Figure 5a shows trends of poleward-edge latitudes of the northern branch in boreal autumn, derived from 10 model simulations. 7 of the models yield northward expansion, while the other 3 show equatorward shrinking. Averaged magnitude of poleward expansion among the 10 models is about 0.33º in latitude, weaker than that derived from AMIP simulations. For the southern branch in austral autumn, 8 of 10 models show equatorward shrinking of the southern branch (Figure 5b), and 2 models show poleward expansion. However, our analyses show that the annual-mean yields weak poleward expansions of the southern branch, indicating that IPCC-AR4 simulations still generate poleward expansion of the southern branch, though the simulations could not capture the seasonality of poleward expansion in reanalyses. The annual-mean of the northern branch also shows poleward expansion.

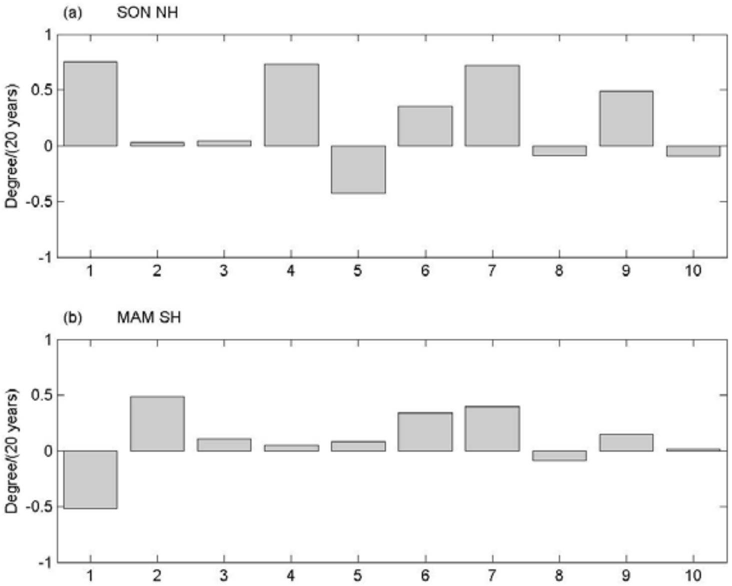

Figure 5. Same as Figure 3, except for IPCC-AR4 simulations. The bars from left to right correspond to MPI-ECHAM5, UKMO-HADCM3, NCAR, GISS-EH, GISS-ER, GFDL-CM20, GFDL-CM21, NCAR-CCSM30, UKMO-HADGEM1, GISS-AOM, respectively

Figure 6a shows trends in the maximum MMS values of the northern Hadley-circulation branch in boreal winter, derived from the same 10 model simulations. 8 of the 10 models display weakening, one model has almost no changes, and only one model shows weakly strengthening. For the southern branch in austral winter (Figure 6b), 5 models display weakly weakening, while another 5 shows weak strengthening. Average of the 10 models yields a trend close to zero. However, for annual mean, average of the 10 models shows weakly weakening. Overall, IPCC-AR4 simulations yield a weakened Hadley circulation, contradicting with that in reanalyses.

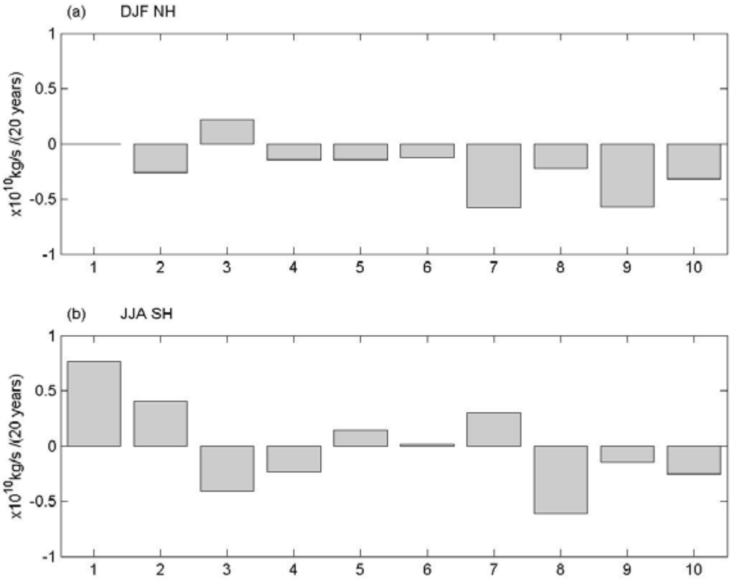

Figure 6. Same as Figure 4, except for IPCC-AR4 simulations. The bars are in the same order as that in Figure 5.

5. Discussion and conclusions

Using three reanalysis datasets and two kinds of GCM simulations, we have examined decadal changes in both width and strength of the Hadley circulation. In general, both reanalyses and simulations show consistent results that the Hadley circulation has poleward expansion in both hemispheres since 1979. The results here, along with other observational results such as trends in total ozone (Hudson et al., 2006), OLR trends (Hu and Fu, 2007), and trends in tropopause heights (Seidel and Randel, 2007), all suggest that the Hadley circulation has poleward expansion since 1979.

However, the signal of intensification of the Hadley circulation derived from NCEP/NCAR and ERA40 reanalyses is not supported by the results from NCEP/DOE reanalysis and GCM simulations. Moreover, most GCM simulations show weakening of the Hadley circulation. These inconsistent results of intensity changes in the Hadley circulation suggest that the intensification in NCEP/NCAR and ERA40 could be artificial due to problems of the reanalysis models and other reasons. Held and Soden (2006) pointed out that the ERA40 reanalysis model produced unrealistically large positive trend in tropical precipitation, and that the artificially increased tropical precipitation would lead to stronger upward motions in the tropics and thus a strong Hadley circulation. Therefore, the strong intensification of the Hadley circulation in ERA40 may be artificial. Mitas and Clement (2006) suggested that the intensification of the Hadley circulation in NCEP/NCAR might be due to the weak cooling trends in the tropical upper troposphere, which cause stronger hydrostatic instability. Thus, upward tropical motions become stronger, which consequently leads to a strong Hadley circulation. They pointed out that the weak cooling trends are due to the update of sounding instruments for observations.

AMIP simulations reproduced poleward expansion of the Hadley circulation in both hemispheres and captured the seasonality very well. IPCC-AR4 AOGCM simulations for the 20th century yield poleward expansion of the northern branch in the same season (boreal autumn). They also reproduced poleward expansion of the southern branch based on the annual mean, though they do not capture the seasonality. The agreement between the reanalyses and simulations suggest that the observed broadening of the Hadley circulation might be a response to increasing greenhouse gases. However, it is important to point out that magnitudes of poleward expansion generated in GCM simulations are much weaker than that in reanalyses and other observational datasets. In particular, the magnitudes in IPCC-AR4 simulations, which include both SST and tropospheric warming, are even weaker than that in AMIP simulations. The difference between the AMIP-type and coupling GCM simulations is likely because the coupling models could not reproduce the observed SST warming. At current stage, it is not clear why GCMs are unable to reproduce magnitudes of poleward expansion comparable to observations.

One important question is how global greenhouse warming caused the broadening of the Hadley circulation. Hu and Fu (2007) argued that the observed poleward expansion is due to the weakening of baroclinic instability in the extratropics. It is because global warming is not uniform, with weaker warming in the tropics and stronger warming at higher latitudes (Fu et al., 2006), which leads to a weakening of meridional temperature gradients in the extratropics. Consider that changes in meridional temperature gradients must cause changes in baroclinic wave activity. A weaker temperature gradient would cause weaker baroclinic wave activity, which allows angular momentum conservation extending further poleward (Held, 2000). Thus, the Hadley circulation becomes broader. This qualitative argument needs to be quantified in further studies. Moreover, whether the much weaker magnitudes of poleward expansion in GCM simulations are due to the lack of capability of GCMS in generating realistic meridional temperature gradients also needs to be confirmed.

References

1. J. Y. Chen, B. E. Carlson, and A. D. Del Genio, *Science*, **295**, 838-841 (2002).
2. H. F. Diaz, and B. Bradley, *The Hadley Circulation: Present, Past and Future*. Kluwer Academic Publishers, the Netherlands (2004).
3. Q. Fu, C. M. Johanson, J. M. Wallace, and T. Reichler, *Science*, **312**, 1179 (2006).
4. Q. Fu, C. M. Johanson, S. G. Warren, and D. J. Seidel, *Nature*, **429**, 55-58 (2004).
5. W. L. Gates, J. S. Boyle, C. Covey, et al., *Bull. Am. Meteorol. Soc.*, **80**, 29-55 (1999).
6. I. M. Held, and A. Y. Hou, *J. Atmos. Sci.*, **37**, 515-533 (1980).
7. I. M. Held, *Proc. Program in Geophysical Fluid Dynamics.* http://gfd.whoi.edu/proceedings/2000/PDFvol2000.html (2000).
8. I. M. Held, and B. J. Soden, *J. Clim.*, **19**, 5686– 5699 (2006).
9. J. R. Holton, *An Introduction to Dynamic Meteorology*. Academic Press, New York (1994).
10. Y. Hu, K.-K., Tung, and J. Liu, *J. Clim.*, **18**, 2924-2936 (2005).
11. Y. Hu, and Q. Fu, *Atmos. Chem. and Phys.*, **7**, 5229-5236 (2007).
12. R. D. Hudson, M. F. Andrade, M. B. Follette, and A. D. Frolov, *Atmos. Chem. Phys.*, **6**, 5183–5191 (2006).
13. E. Kalnay, M. Kanamitsua, R. Kistlera, *et al.*, *Bull. Am. Meteorol. Soc.*, **77**, 437-471 (1996).
14. M. Kanamitsu, W. Ebisuzaki, J. Woollen, *et al.*, *Bull. Am. Meteorol. Soc.*, **83**, 1631-1643 (2002).
15. R. S. Lindzen, *Ann. Rev. Fluid Mech.*, **26**, 353-378 (1994).
16. J. Lu, G. A. Vecchi, and T. Reichler, *Geophys. Res. Lett.*, **34**, L06805, doi:10.1029/2006GL028443 (2007).
17. C. M. Mitas, and A. Clement, *Geophys. Res. Lett.*, **32**, L03809, doi: 10.1029/2004GL021765 (2005).

18. C. M. Mitas, A. Clement, *Geophys. Res. Lett.*, **33**, L01810, doi: 10.1029/2005GL024406 (2006).
19. X. Quan, H. F. Diaz, and M. P. Hoerling, The conference on the Hadley circulation: Present, Past and Future, November 12-15, 2002, Honolulu, Hawaii (2002).
20. D. J. Seidel, and R. J. Randel, *J. Geophys. Res.*, **112,** D20113 (2007).
21. D. J. Seidel, Q. Fu, W. J. Randel, T. J. Reichler, *Nature Geoscience,* **1**, 21–24 (2008).
22. S. Solomon, et al. *Climate Change 2007; The Physical Basis* (Cambridge University Press, Cambridge, UK (2007).
23. K. E. Trenberth, *Science*, **296**, 2095a (2002).
24. S. M. Uppala, P. W. Kallberg, A. J. Simmons, *et al.*, Quart. *J. Roy. Meteor. Soc.*, **131**, 2961-3012 (2005).