



Expansion of the Hadley cell under global warming

Jian Lu,^{1,2} Gabriel A. Vecchi,³ and Thomas Reichler⁴

Received 11 October 2006; revised 9 February 2007; accepted 21 February 2007; published 24 March 2007.

[1] A consistent weakening and poleward expansion of the Hadley circulation is diagnosed in the climate change simulations of the IPCC AR4 project. Associated with this widening is a poleward expansion of the subtropical dry zone. Simple scaling analysis supports the notion that the poleward extent of the Hadley cell is set by the location where the thermally driven jet first becomes baroclinically unstable. The expansion of the Hadley cell is caused by an increase in the subtropical static stability, which pushes poleward the baroclinic instability zone and hence the outer boundary of the Hadley cell. **Citation:** Lu, J., G. A. Vecchi, and T. Reichler (2007), Expansion of the Hadley cell under global warming, *Geophys. Res. Lett.*, 34, L06805, doi:10.1029/2006GL028443.

1. Introduction

[2] The Hadley cell (HC) plays a pivotal role in the earth's climate by transporting energy and angular momentum poleward and by organizing the three dimensional tropical atmospheric circulation. The locations of the large-scale subtropical dry zones and the major tropical/subtropical deserts of the globe are largely determined by the subsiding branches of the HC. Thus, understanding how the structure and intensity of the HC and the associated subtropical dry zones may change under the greenhouse gas (GHG)-induced global warming is a topic of substantial interest.

[3] The detailed response of the HC to increasing GHG is complex, as the HC is influenced by many factors, involving tropical heating processes [e.g., *Mitas and Clement*, 2006], the atmospheric stability [e.g., *Schneider*, 1977], extra-tropical eddy dynamics [e.g., *Walker and Schneider*, 2006], and total atmospheric moisture [*Frierson et al.*, 2006]. To date, studies of the long term behavior of the HC, and the extent to which GHG forcing is relevant remain inconclusive. Atmospheric reanalyses show a statistically significant intensification of their Hadley circulation throughout the second part of the 20th century [*Mitas and Clement*, 2005]. However, this intensification is not found in the rawinsonde data, nor in most 20th century simulations

using both coupled or atmosphere-only general circulation models (GCMs) [*Mitas and Clement*, 2005, 2006]. Meanwhile, simple physical arguments [e.g., *Betts*, 1998; *Knutson and Manabe*, 1995; *Held and Soden*, 2006] predict a slowdown of the overall tropical overturning circulation under global warming. Such a slowdown seems to be a robust feature in GCMs [*Vecchi and Soden*, 2007], and has been identified in observational analyses of the Walker circulation [*Vecchi et al.*, 2005; *Zhang and Song*, 2006].

[4] However, it remains to be seen whether it also projects onto the zonally averaged part of the circulation. Analysis of the satellite observations indicates a poleward expansion of the HC over the past 27 years [*Fu et al.*, 2006]. The extent to which this observed widening of the HC is primarily a response to GHG warming is not clear and warrants further investigation.

[5] Here, we investigate the response of the HC to global warming using 21st century increasing GHG scenarios from the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC). The diversity of the numerical schemes and parameterizations of the AR4 models provides a unique framework for understanding the response of the HC to GHG increases. In this study we show that there is a robust poleward expansion and weakening of the Hadley circulation across all models, and we identify a possible mechanism for this behavior.

2. Data and Methods

[6] Gridded global monthly precipitation, evaporation, surface air temperature, surface wind, temperature, meridional wind, and 500hPa pressure velocity (ω_{500}) were retrieved from the AR4 archive website (available at <http://www-pcmdi.llnl.gov>), and annual means were formed for the analysis. Most of our analysis was based on output from the A2 scenario which is at the upper end of GHG emission (the CO₂ concentration reaches 800 ppm at the end of the 21st century), two less aggressive scenarios were also explored (A1B with CO₂ stabilization at 720ppm and B1 with CO₂ stabilization at 550ppm). Only the first ensemble member of each of the 14–15 models (depending on the availability of the variables) was used. To identify the climate change response, we compared the first and last twenty years of the 21st century, i.e., (2081–2100) minus (2001–2020).

[7] To determine the poleward edges of the HC, we computed the zonal-mean mass flux stream function (ψ) by vertically integrating the zonal-mean density-weighted meridional wind component from the top model level downward. We first determined the maximum of the absolute value of this stream function at 500 hPa (ψ_{500}), and then identified the edges of the HC as the first latitude poleward of the maximum at which ψ_{500} became zero. An alternative definition of the HC edge as the transition

¹Climate and Global Dynamics Division, National Center for Atmospheric Research, University Corporation for Atmospheric Research, Boulder, Colorado, USA.

²University Corporation for Atmospheric Research Visiting Scientist Program, Geophysical Fluid Dynamics Laboratory, NOAA, Princeton University, Princeton, New Jersey, USA.

³Geophysical Fluid Dynamics Laboratory, National Oceanic and Atmospheric Administration, Princeton University, Princeton, New Jersey, USA.

⁴Department of Meteorology, University of Utah, Salt Lake City, Utah, USA.

latitude from zonal-mean surface easterlies to westerlies was also tested, and did not influence the principal conclusions of this study. Therefore, only the results from the ψ_{500} based definition are presented here. The edge of the subtropical dry zone in each hemisphere was identified as the latitude where the zonal mean precipitation minus evaporation ($P-E$) field crosses zero poleward of the subtropical minimum.

[8] Theories of the Hadley circulation suggest that the meridional extent of the HC should scale with the height of the tropopause [Held and Hou, 1980] (The general circulation of the atmosphere, 2000 Program in Geophysical Fluid Dynamics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, available at <http://gfd.who.edu/proceedings/2000/PDFvol2000.html>). This height was computed from temperature data as the lowest pressure level at which the lapse rate decreases to $2^\circ\text{C}/\text{km}$, following the algorithm of Reichler *et al.* [2003] and the *World Meteorological Organization* [1957] definition.

[9] To account for the different climate sensitivities of each model, at times we normalized the various quantities by the corresponding changes in global mean surface temperature of each model.

3. Results

[10] We first examine the response of global hydrological cycle in scenario A2 by looking at the field of precipitation minus evaporation ($P-E$, Figure 1); for clarity, areas of

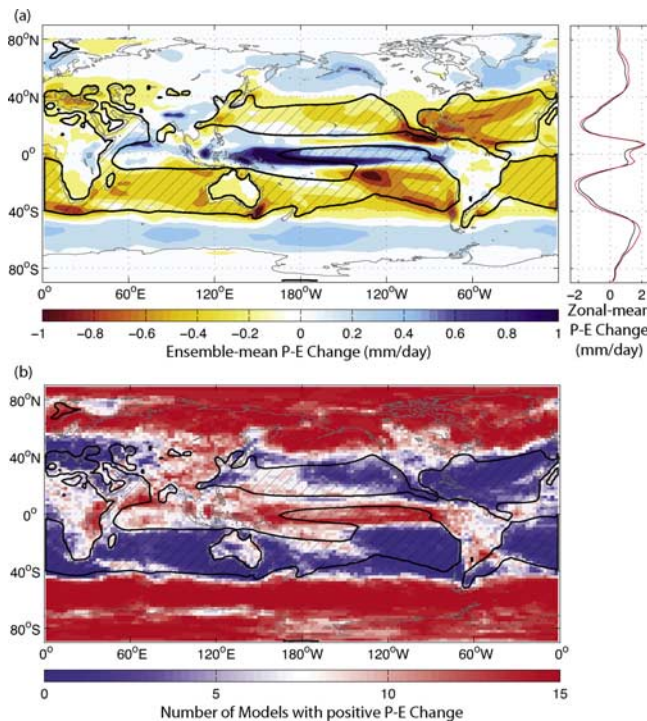


Figure 1. (a) Multi-model ensemble mean $P-E$ in the A2 scenario. Shading indicates the difference between the first and the last 20 years of the 21st century and the black line denotes the 0-isopleths averaged from 2001 to 2020. The zonal mean averaged over 2001–2020 (black) and 2081–2100 (red) is shown; units are mm/day. (b) Number count out of the total 15 models that simulate a moistening (i.e., $\Delta(P-E) > 0$) at each grid point.

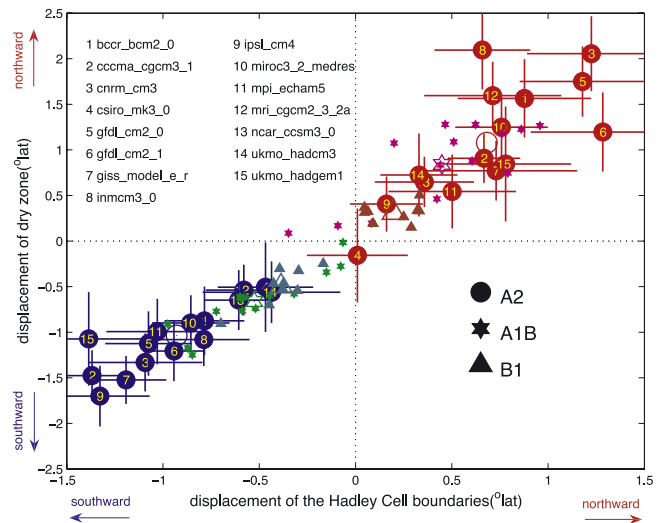


Figure 2. The breakdown by models and scenarios of the displacement of the northern (warm colors) and southern (cold colors) edges of the subtropical dry zone (y-axis) versus that of the HC (x-axis). The circles, hexagrams, and triangles denote the changes (2081–2100 minus 2001–2020) estimated from the A2, A1B, and B1 scenarios, respectively. The open symbols denote the multi-model ensemble mean values. The cross on each circle shows the 95% confidence interval of the estimated displacements using Student’s t-test.

negative climatological $P-E$ are hatched. The overall characteristic of the multi-model ensemble mean hydrological response to global warming is a reinforcement of the global climatological background pattern [Held and Soden, 2006]. In addition, there is a general tendency for a poleward expansion of the subtropical dry zone (areas encircled by the 0 isopleths of $P-E$). Counting the number of models that simulate a positive $P-E$ change (Figure 1b), one can see that the overall pattern of $P-E$ change is robust across most models and that the model number count bears great resemblance to the trend pattern itself.

[11] The poleward expansion of the subtropical dry zone is strongly tied to the poleward expansion of the HC (see Figure 2). Based on the 38 simulations from the three scenarios (A2, A1B, B1), about 85% (72%) of the spread in the poleward displacement of the subtropical dry zones in the southern (northern) hemisphere can be explained by a linear relation to the displacements of the outer boundaries of the HC. The ensemble mean response of the A2 scenario (open circle) shows that the edges of the subtropical dry zone displace poleward by $\sim 1^\circ$ in each hemisphere. A similar poleward expansion can be found in the subtropical downward ω_{500} field (not shown). The magnitude of the expansion is a function of the GHG forcing, with similar but weaker expansions found in scenarios A1B (hexagrams) and B1 (triangles).

[12] Another important aspect of the HC response to global warming is the reduction of its intensity (auxiliary material Figure S1).¹ The models show a tendency for a HC

¹Auxiliary materials are available in the HTML. doi:10.1029/2006GL028443.

weakening at rates between 0–4%/K, with a mean of 1.2%/K. It is important to note that these models project a slowdown of the entire tropical overturning circulation, particularly the Walker circulation [Vecchi and Soden, 2007], in a manner consistent with the Claussius-Clapeyron scaling by Held and Soden [2006]. Meanwhile, weakening of the HC ($\sim 1\%/K$) is substantially smaller than that of the Walker circulation ($\sim 5\%/K$) [Vecchi and Soden, 2007] for reasons yet to be understood. Interestingly, a similar anisotropism is also found in the reduction of the zonal mean and the zonally asymmetric components of the tropical convective mass flux [Held and Soden, 2006].

4. Possible Mechanisms for HC Expansion

[13] Two alternative views on the controls of the HC have guided much of the understanding of the width of the HC. On one hand, nearly inviscid theory for axisymmetric circulation (no eddies) [Held and Hou, 1980] predicts that the meridional extent of the HC scales as

$$\phi_H \sim \left(\frac{gH_t \Delta_h}{\Omega^2 a^2 \theta_0} \right)^{\frac{1}{2}}, \quad (1)$$

where H_t is the height of the tropical tropopause, θ_0 is global mean temperature, Δ_h is the equator-to-pole surface potential temperature difference in radiative equilibrium, and other parameters have their conventional meanings. This scaling relation, which suggests no dependence on static stability, is derived by assuming that (1) the zonal wind in the upper branch of the HC is angular-momentum conserving and (2) the HC is energetically closed, so that the diabatic heating in the ascent regions is balanced by the diabatic cooling in the descent regions. The second view sees the width of the HC as being determined by the poleward extent to which the angular-momentum conservation continues until the resulting vertical shear becomes baroclinically unstable (available at <http://gfd.who.edu/proceedings/2000/PDFvol2000.html>). Solving the equation between the angular momentum conserving zonal wind and the baroclinically critical zonal wind yields an alternative scaling for the width of the HC:

$$\phi_H \propto \left(\frac{NH_e}{\Omega a} \right)^{\frac{1}{2}}, \quad (2a)$$

if using the two-layer model's criterion [Phillips, 1954] for instability, or

$$\phi_H \propto \left(\frac{NH_e}{\Omega^2 a} \right)^{\frac{1}{3}}, \quad (2b)$$

if using a more general criterion based on the Eady growth rate, both implying a positive proportional relationship with NH_e . The Eady growth rate is used here in the vertical averaged sense, i.e., fu/NH_e , where u is the zonal wind difference between the upper and lower troposphere, H_e the local tropopause height, N the vertically averaged Brunt-Väisälä frequency, indicative of the tropospheric gross static stability. If the scaling relation (1) applies to the HC expansion under GHG forcing, variations of the HC width

should be proportional to the tropical tropopause height. On the other hand, if the scaling (2) applies, one may expect the extent of the Hadley circulation to be sensitive to the gross stability and the tropopause height near the poleward boundary of the circulation.

[14] First, to test the extent to which scaling relation (1) controls the models' HC expansion through changing the tropical tropopause height (TTH), we plot for each model the change in TTH during the 21st century against that of the HC extent, the former being estimated as the negative of the pressure anomalies at the tropopause and averaged within 20° to the equator, and the latter defined as the distance between the southern and northern edges of the HC. Both quantities were normalized by the increase of the global mean temperature seen in the individual models during the 21st century. Comparing different models, the individual long-term trends in HC extent show only a small correlation to the trends in TTH (Figure 3a). In fact, within each model, the detrended annual mean time series of TTH and HC extent tend to be anti-correlated, in stark contrast to the positive correlations of the time series with trend (Figure 3b). This hints that distinct mechanisms govern the long-term widening of the HC under global warming and its interannual variability. Additional composite analysis using the simulations from GFDL CM2.1 model (not shown) reveals that, at interannual time scales, anomalously high TTH is associated with El Niño-like conditions — stronger and narrower than normal tropical heating and more intense Hadley overturning circulation. This is consistent with previous findings [Chang, 1995; Seager et al., 2003] that the more accentuated tropical convective heating during El Niño usually drives a stronger and narrower HC. The contraction of the Hadley cell under the El Niño condition may be interpreted as the consequence the intensified subtropical jet, which attracts equatorward the critical latitudes of the eddy propagation and the associated eddy-driven subtropical subsidence near the outer boundary of the Hadley cell descent [Seager et al., 2003; G. Chen, personal communication, 2006].

[15] The extratropical tropopause height (ETH, averaged over 35° – 55°), is found to be closely related to the variation of the HC extent not only within each model (Figure 3d), but also in the comparison of the long-term trend among models (Figure 3c). A similar relationship has been found between the HC extent and the gross stability. Indeed, the ETH is very strongly correlated with the local gross stability (with correlations of ~ 0.95) within most models examined and hence can be thought of as a good proxy of the ETH. The change in mid-latitude tropopause height (or stability) not only explains over 60% of the variance in the spread of the HC widening across the AR4 models, but also accounts for the consensus HC expansion at a rate of 1.2° per 10hPa rise in the ETH in the A2 scenario. The relevance of the ETH to the HC extent in the natural climate variability can also be readily discerned from their correlations of the detrended time series in Figure 3d.

[16] From this analysis, one is tempted to argue that scaling relation (2) is a better model for the extent of the HC. The HC extent in the present-day climate may be interpreted as being limited by the latitude at which the thermally driven wind becomes baroclinically unstable, rather than by the energetic closure of the thermally driven

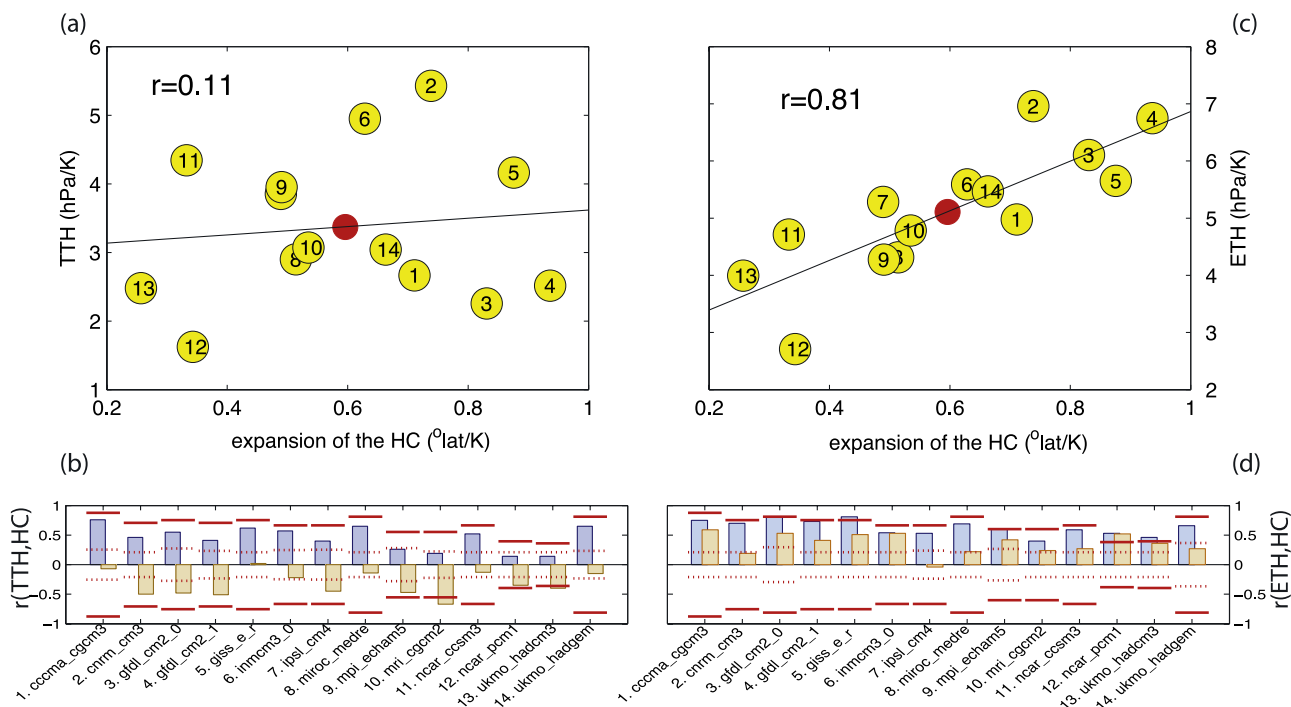


Figure 3. The relationship of (a–b) the tropical (20°S – 20°N) tropopause height (TTH); (c–d) the extra-tropical (35°S – 55°S and 35°N – 55°N) tropopause height (ETH) with the extent of the HC for 14 models from the A2 scenario. Positive tropopause height value represents rise of tropopause. Figures 3a and 3c show the differences between (2081–2100) and (2001–2020), normalized by the corresponding change in the global mean temperature. The red dots denote the multi-model ensemble mean values. Figures 3b and 3d show the correlation coefficients between the full (blue bars) and detrended (sandy bars) time series of the HC extent and TTH (Figure 3b) and ETH (Figure 3d). The horizontal lines indicate the $P=0.05$ confidence level of the correlation for each model based on Student's t-test. During the computation of the confidence levels, the reduction of effective degrees of freedom due to the autocorrelations of the time series has been considered following formula (30) by Bretherton *et al.* [1999]. The solid (dotted) lines are estimated from the full time series containing trend (detrended time series).

cell. Under global warming conditions, rising tropospheric static stability, which is an established consequence of moist thermodynamics, stabilizes the subtropical jet streams at the poleward flank of the Hadley Cell to what is required by baroclinic instability considerations (see auxiliary material Figure S2), and consequently, the Hadley Cell extends poleward.

5. Concluding Remarks

[17] In response to increased GHG forcing, we find a robust weakening and poleward expansion of the Hadley circulation in simulations of the 21st century climate taken from the A2 scenario of the IPCC AR4 project. In accord with the movement of the HC, the subtropical dry zones also expand poleward. Further analysis suggests that the consensus of the HC expansion in the AR4 models is unlikely to originate from tropical processes, despite the fact that tropical heating is effective in driving the variation of the HC at interannual time scales, and that it accounts for significant part of the inter-model variability in HC expansion (not shown). We find that extratropical tropopause height, which is a good proxy of the gross static stability, varies in concert with the width of the HC on both the interannual and longer time scales. The increase in the gross stability near the subtropics acts to suppress baroclinic

instability, which is a critical factor controlling the limits of the outer boundaries of the HC. The extratropical stabilization inhibits the breakdown of the thermally driven cell, allowing it to reach higher latitudes, as a result the edges of the HC expand poleward.

[18] The conclusion of the dynamics controlling the poleward expansion of the HC based on this simple scaling analysis can only be taken to be tentative, given the assumption of conservation of angular momentum and that only the annual means have been analyzed. Further analysis is underway examining the seasonality of these scaling relationships and the effect of relaxing the assumption of angular momentum conservation, and will be reported elsewhere.

[19] The latitudinal distribution of the lower tropospheric warming in the A2 scenario runs shows remarkable qualitative resemblance to observational estimates from the microwave sounding unit (MSU) data gathered over the period 1979–2005 [Fu *et al.*, 2006], both sharing features such as a local minimum warming near the equator, a local maximum warming in the subtropics, and amplified warming in the Northern Hemisphere high-latitudes. Fu *et al.* [2006] estimated the amount of latitudinal widening of the HC over the period 1979–2005 as $\sim 2^{\circ}$ latitude. Over the same period the increase in global temperature was about 0.5°C , so that the widening of the HC amounts to $\sim 4^{\circ}$

latitude per degree warming. This is much greater than what we find in the simulations of the AR4 A2 scenario ($\sim 0.6^\circ$ latitude/K). Thus, the observed expansion of the Hadley circulation during the late 20th century may, to a large degree, be attributed to factors other than the GHG-induced global warming, such as ozone depletion and/or natural climate variability. It is also possible that the contribution from the GHG forcing may be larger than the ensemble mean suggests, given the large spread between the individual model simulations (Figure 3).

[20] **Acknowledgments.** We thank Kirk Bryan, Isaac Held, Dargan Frierson, and Qian Song for their perceptive comments and useful discussions during the formative stage of this paper. The comments from two anonymous reviewers are also appreciated. We acknowledge the international modeling group for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modeling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data and analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy. J. Lu is supported by the Visiting Scientist Program of the University Corporation for Atmospheric Research (UCAR). T. Reichler is partially supported by NSF grant ATM 0532280.

References

- Betts, A. K. (1998), Climate-convection feedbacks: Some further issues, *Clim. Change*, *39*, 35–38.
- Bretherton, C. S., M. Widmann, V. P. Dymnikov, J. M. Wallace, and I. Blade (1999), The effective number of spatial degrees of freedom of a time-varying field, *J. Clim.*, *12*, 1990–2009.
- Chang, E. K. M. (1995), The influence of Hadley circulation intensity changes on extratropical climate in an idealized model, *J. Atmos. Sci.*, *52*, 2006–2024.
- Frierson, D. M. W., I. Held, and P. Zurita-Gotor (2006), A gray-radiation aquaplanet moist GCM. Part I: Static stability and eddy scale, *J. Atmos. Sci.*, *63*, 2548–2566.
- Fu, Q., C. M. Johanson, J. M. Wallace, and T. Reichler (2006), Enhanced mid-latitude tropospheric warming in satellite measurements, *Science*, *312*, 1179.
- Held, I. M., and A. Y. Hou (1980), Nonlinear axially symmetric circulations in a nearly inviscid atmosphere, *J. Atmos. Res.*, *37*, 515–533.
- Held, I. M., and B. J. Soden (2006), Robust response of the hydrological cycle to global warming, *J. Clim.*, *19*, 5686–5699.
- Knutson, T. R., and S. Manabe (1995), Time-mean response over the tropical Pacific to increased CO₂ in a coupled ocean-atmosphere model, *J. Clim.*, *8*, 2181–2199.
- Mitas, C. M., and A. Clement (2005), Has the Hadley cell been strengthening in recent decades?, *Geophys. Res. Lett.*, *32*, L03809, doi:10.1029/2004GL021765.
- Mitas, C. M., and A. Clement (2006), Recent behavior of the Hadley cell and tropical thermodynamics in climate models and reanalyses, *Geophys. Res. Lett.*, *33*, L01810, doi:10.1029/2005GL024406.
- Phillips, N. A. (1954), Energy transformations and meridional circulations associated with simple baroclinic waves in a two-level, quasi-geostrophic model, *Tellus*, *6*, 273–286.
- Reichler, T., M. Dameris, and R. Sausen (2003), Determining the tropopause height from gridded data, *Geophys. Res. Lett.*, *30*(20), 2042, doi:10.1029/2003GL018240.
- Schneider, E. K. (1977), Axially symmetric steady-state models of the basic state for instability and climate studies, Part II. Nonlinear calculations, *J. Atmos. Sci.*, *34*, 280–296.
- Seager, R., N. Harnik, Y. Kushnir, W. Robinson, and J. Miller (2003), Mechanisms of hemispherically symmetric climate variability, *J. Clim.*, *16*, 2960–2978.
- Vecchi, G. A., and B. J. Soden (2007), Global warming and the weakening of the tropical circulation, *J. Clim.*, in press.
- Vecchi, G. A., B. J. Soden, A. T. Wittenberg, I. M. Held, A. Leetmaa, and M. J. Harrison (2005), Weakening of tropical Pacific atmospheric circulation due to anthropogenic forcing, *Nature*, *441*(7089), 73–76.
- Walker, C. C., and T. Schneider (2006), Eddy-influences on Hadley circulations: Simulations with an idealized GCM, *J. Atmos. Sci.*, *63*, 3333–3350.
- World Meteorological Organization (1957), Meteorology—A three-dimensional science: Second session of the commission for aerology, *WMO Bull.*, *4*, 134–138.
- Zhang, M., and H. Song (2006), Evidence of deceleration of atmospheric vertical overturning circulation over the tropical Pacific, *Geophys. Res. Lett.*, *33*, L12701, doi:10.1029/2006GL025942.

J. Lu and G. A. Vecchi, GFDL, NOAA, Princeton University, P.O. Box 308, Princeton, NJ 08542, USA. (jian.lu@noaa.gov)

T. Reichler, Department of Meteorology, University of Utah, 135 South 1460 East, Room 819 WBB, Salt Lake City, UT 84112-0110, USA.