Recent behavior of the Hadley cell and tropical thermodynamics in climate models and reanalyses

Christos M. Mitas and Amy Clement
Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida, USA

Received 16 August 2005; revised 18 October 2005; accepted 23 November 2005; published 6 January 2006.

[1] The behavior of the Hadley cell and the thermodynamic structure of the tropical atmosphere is analyzed over the period 1979–2000 in climate models and reanalyses. Significant trends in the strength of the Hadley cell are present in reanalyses that are not reproduced by models. Analysis of the thermodynamic structure also shows significant discrepancies between models and reanalyses, the former show warming aloft and increased static stability while the latter show a cooling trend and decreased static stability in the tropical mid-troposphere. Additional energy balance analysis reveals that models and reanalyses have a fundamentally different balance between diabatic heating, circulation and thermodynamic structure over the period 1979–2000. Uncertainties in the observations of tropospheric temperatures as well as potential biases and errors in the climate models raise questions about the true long-term behavior of the thermodynamic structure of the tropical troposphere and the Hadley cell. **Citation:** 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.

1. Introduction

[2] Several recent studies have shown that there are significant trends in the strength of the tropical atmospheric circulation over recent decades in major reanalysis products [*Mitas and Clement*, 2005; *Quan et al.*, 2004; *Tanaka et al.*, 2004]. In particular, *Mitas and Clement* [2005] have shown that the boreal winter Hadley cell in reanalyses has increased in strength by as much as 30% over the last half-century. At present, there is no explanation for such a trend. In fact, *Knutson and Manabe* [1995] used a general circulation model to show that the expected response of the tropical atmosphere to increased greenhouse gas forcing is a *weakening* of the circulation. Those authors argue that the connection between circulation and forcing in the model is via the thermodynamic structure of the tropical free troposphere. They found that the static stability of the upper troposphere in the upward branch of the Hadley cell is inversely proportional to the strength of the cell. Similar results have been found in general circulation model studies of the response to volcanic forcing [*Rind et al.*, 1992] and in simplified modeling studies [*Kim and Lee*, 2001].

[3] Here we use this conceptual framework to compare the behavior of the Hadley cell and thermodynamic structure of the tropical atmosphere over the last two decades in models and reanalyses. We take advantage of a large number of simulations of the late 20th century with coupled and atmosphere-only GCMs that have become available through the upcoming Intergovernmental Panel on Climate Change fourth Assessment Report (IPCC AR4). We document the behavior of the Hadley circulation and thermodynamic structure of the tropical atmosphere in the GCMs, and directly compare it with reanalyses. This comparison is both an important consistency check as well as a potential tool for identifying the relative effects of SSTs and greenhouse gases in forcing this behavior.

0094-8276/06/2005GL024406

2. Model and Reanalyses Data

[4] The Program for Climate Model Diagnosis and Intercomparison (PCMDI) (https://esg.llnl.gov:8443/index.jsp) has archived the model output from over twenty international modeling centers. We analyze output from the following models: BCC-CM1, BCCR-BCM2.0, CGCM3.1(T47), CGCM3.1(T63), CNRM-CM3, CSIRO-Mk3.0, GFDL-CM2.0, GFDL-CM2.1, GISS-AOM, GISS-EH, GISS-ER, FGOALS-g1.0, INM-CM 3.0, IPSL-CM4, MIROC3.2(hires), MIROC3.2(medres), ECHAM5/MPI-OM, MRI-CGCM2.3.2, CCSM3, PCM, UKMO-HadCM3, and UKMO-HadGEM1. More information on the models may be found on the IPCC website (http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php).

[5] All of the 20th century coupled simulations (20C3M) were forced with historical changes in greenhouse gases, and some of the models also include other external forcings (e.g., sulfate aerosols, volcanic and solar forcings) [*Santer et al.*, 2006]. The AMIP simulations include only the atmospheric component of the GCMs with SSTs and sea-ice distribution prescribed from the observational record. We analyze output from 22 20C3M and 12 AMIP models. Sixteen of the 20C3M models and four of the AMIP models have multiple simulations. The number of realizations which have reported the variables of meridional wind and temperature are 69 and 25, for 20C3M and AMIP respectively. In Section 4, we include results from only 66 20C3M simulations which had vertical velocity available. The reanalyses data sets used in this study include the NCEP/NCAR reanalysis, and the ECMWF 40-year reanalysis project (ERA40). Results are presented for the common period to model simulations and reanalyses, which is 1979–2000.

3. Hadley Cell Strength and Tropical Thermodynamic Structure

[6] Figure 1 presents the probability density functions (PDFs) of the Northern Hemisphere winter (DJF) linear

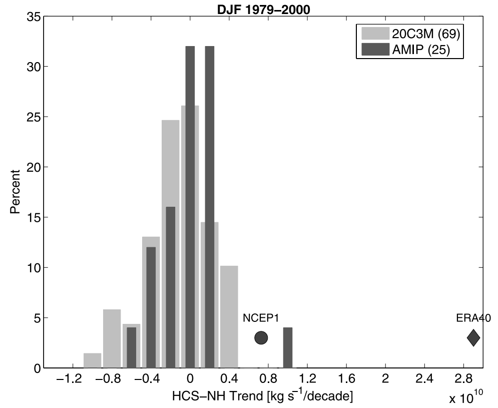

Figure 1. PDFs of Northern hemisphere winter (DJF) linear trends for the period 1979–2000 of the maximum mean meridional streamfunction (NH Hadley Cell Strength) of 25 AMIP and 69 20C3M simulations. Superposed are the values for NCEP/NCAR and ERA40 reanalyses.

trend between 1979 and 2000 of the maximum of the mean meridional streamfunction for AMIP and 20C3M simulations. About 67% (62%) of the 94 model simulations show decrease or no increase of their Hadley cell strength for DJF (JJA). We also show the values of trend for the NCEP/NCAR and ERA40 reanalyses: 7.28e+09 and 29.02e+09 [kg/s/decade], respectively, both significant at 92.5% confidence level, with autocorrelation taken into account in the manner of *Santer et al.* [1999]. It is clear that most of AMIP and 20C3M simulations show either negligible change or a decrease in the Hadley circulation, consistent with the previous results of *Knutson and Manabe* [1995]. Similar but less statistically significant results are obtained for the Southern Hemisphere winter (JJA) Hadley cell for NCEP/NCAR and ERA40: -0.29×10^9 and -12.5×10^9 [kg/s/decade], respectively, significant at 70% confidence level; hence our focus on the NH winter.

[7] To investigate the source of the discrepancy between the models and the reanalyses we examine the trend in thermodynamic structure of the tropical troposphere. The DJF trends of potential temperature (θ) for the reanalyses are shown in Figure 2. The most notable feature is the cooling trend of the mid-tropospheric tropical region. The magnitude and spatial structure of the trend for both reanalyses when computed over different 20-year segments of the late 20th century are robust. The reanalyses appear to be consistent with the radiosonde data sets of NOAA and UKMO which show cooling of the middle to upper tropical troposphere [*Santer et al.*, 2005]. However, it should be noted that recent temperature measurements show upper tropospheric warming in the deep tropics in step with the surface temperature warming [*Santer et al.*, 2005; *Sherwood et al.*, 2005]. Contrary to the reanalyses trends, the ensemble of AMIP simulations (not shown) shows a distinct warming throughout the tropical free troposphere. This is consistent with a moist adiabatic adjustment to the warming surface temperatures. The coupled simulations ensemble shows a similar pattern of warming (not shown), although the trend is ~65% larger (~0.25 [K/decade] in the tropical mid troposphere) than AMIP (~0.15 [K/decade]), which may be related to the larger surface warming trend in those models (0.13 [K/decade] for 20C3M at 1000 hPa, and 0.11 [K/decade] for AMIP).

[8] The trends in potential temperature affect the static stability ($\sigma = \partial\theta/\partial p$). In Figure 3, we show the PDFs for AMIP and 20C3M of the DJF trend in static stability, averaged over 850–500 hPa and 5N–15S -a representative region of the DJF upward branch of the Hadley cell. We also superpose the averaged values for the NCEP/NCAR and ERA40 reanalyses. Note that the static stability is a negative quantity, hence a negative trend denotes strengthening, while a positive one denotes weakening. It is clear that almost all the 20C3M and the whole set of AMIP simulations show a strengthening of mid-level static stability, while the reanalyses show a marked weakening, particularly ERA40. Figures 1 and 3 are indicative of the inversely proportional relationship between the Hadley cell strength and the tropical mid-tropospheric static stability. In particular, the larger reduction of static stability in ERA40 is accompanied by a larger increase in Hadley cell intensity than in NCEP/NCAR. In the next section, we analyze the

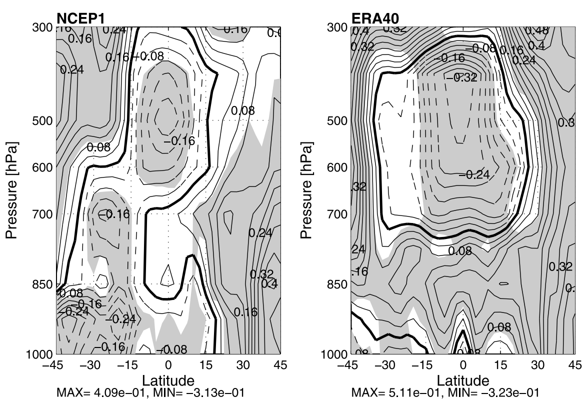

Figure 2. DJF trend of potential temperature for the period 1979–2000 for NCEP/NCAR (left) and ERA40 (right). Shaded regions show trends which are significant at the 90% confidence level.

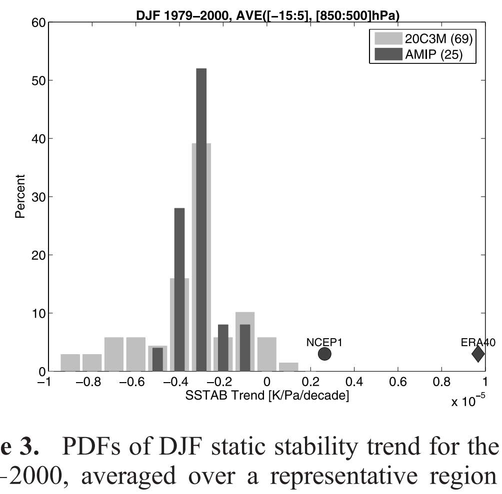

Figure 3. PDFs of DJF static stability trend for the period 1979–2000, averaged over a representative region of the upward branch of the Hadley cell (850–500 hPa, 5N–15S) for 25 AMIP and 69 20C3M simulations. Superposed are the values for the NCEP/NCAR and ERA40 reanalyses.

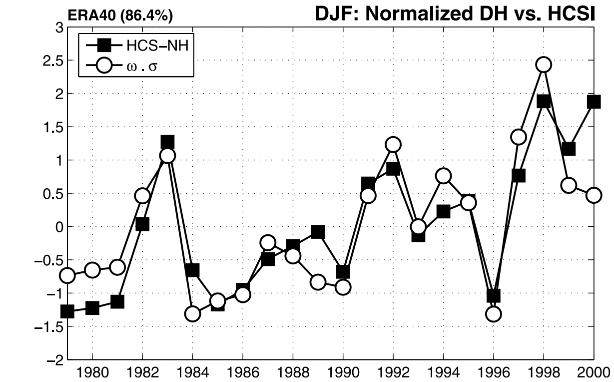

Figure 4. Normalized Hadley cell strength index and diabatic heating averaged over a representative region of the upward branch of the Hadley cell (700–400hPa, 5N–15S) for ERA40's DJF. The correlation coefficient between the two time series is displayed.

energy balance in order to illustrate the connection between circulation and thermodynamic structure.

4. Tropical Diabatic Heating

[9] The thermodynamic equation in the tropics may be significantly simplified because of the absence of eddies and the weak horizontal temperature gradient, to a balance between diabatic heating (H) and adiabatic cooling: $H \approx \omega \cdot \sigma$. Knowledge of the monthly mean vertical velocity (ω) and static stability ($\sigma = \partial\theta/\partial p$) is largely sufficient to describe the low-frequency behavior of the diabatic heating in the seasonal upward branch of the Hadley cell, i.e., the tropical mid-troposphere of the summer hemisphere [*Knutson and Manabe*, 1995].

[10] In Figure 4 the DJF Hadley cell strength index is shown together with an appropriate average of the diabatic heating proxy ($\omega \cdot \sigma$, averaged over 400–700 mb, 5N–15S) for the northern winter season from 1979 to 2000, for ERA40. The correlation of the year-to-year indices is in the order of 85%. The signature of the 1982–1983, 1992–1993, and 1997–1998 ENSOs are clear in both time series. Moreover, they show upward trends indicating strengthening of the circulation coincident with increased diabatic heating, (note that ERA40 has a larger trend than NCEP- not shown). The AMIP and 20C3M simulations also show a strong correlation of diabatic heating and Hadley cell strength (ensemble mean 80.3% and 60.1%, respectively, and ensemble standard deviation 11.3% and 18.1%, respectively).

[11] The long-term trend in diabatic heating may be separated into two contributions, one from the changes in static stability $\omega_0 \cdot \Delta\sigma$, and one from the changes in circulation $\Delta\omega \cdot \sigma_0$:

$$\Delta H \approx \Delta(\omega \cdot \sigma) = \omega_0 \cdot \Delta\sigma + \Delta\omega \cdot \sigma_0 + \Delta\omega \cdot \Delta\sigma \cong \omega_0 \cdot \Delta\sigma + \Delta\omega \cdot \sigma_0,$$

where the zero subscript denotes time averaging, $\Delta(\cdot)$ indicates the trend, and we neglect the product of trends, which is small. This simple separation enables us to identify changes in diabatic heating related with either variations in dynamics or thermodynamics.

[12] Figure 5 shows the PDFs of the terms of the above equation for the models and reanalyses. The upper panel shows the PDF of the first term on the RHS, $\omega_0 \cdot \Delta\sigma$, i.e., the variation in diabatic heating related to thermodynamics. The reanalyses values (both negative) are of the opposite sign of the model values, consistent with Figure 3. (Note that since ω_0 is negative, the quantities shown in Figures 3 and 5 are of opposite sign.) The middle panel shows the PDF of the second term on the RHS, $\Delta\omega \cdot \sigma_0$, i.e., the variation related to dynamics. This term is analogous to the Hadley cell strength index shown in Figure 1, since the streamfunction that is used to calculate the index contains information about the vertical velocity. There is a larger spread in this term than there is in the streamfunction, because $\Delta\omega$ exhibits complicated spatial structure and large ensemble standard deviation (not shown), while the streamfunction is an integrated quantity. Nonetheless, ERA40 lies at the extreme end of the model PDF, and NCEP/NCAR is larger than most of the models. The lower panel presents the PDF of the trend of the total diabatic heating proxy, $\Delta H \approx \Delta(\omega \cdot \sigma)\ \ \omega_0 \cdot \Delta\sigma + \Delta\omega \cdot \sigma_0$. Most of the simulations have smaller trends than the reanalyses, but there is less disagreement between the models and reanalyses in this term. To summarize, the models and reanalyses have a fundamentally different balance between diabatic heating, circulation and thermal structure changes over 1979–2000: In the AMIP and 20C3M simulations, the change in diabatic heating is small, however a marked warming of the upper tropical troposphere causes a stability change which must be balanced by a somewhat slower Hadley circulation. On the contrary, the reanalyses exhibit an increased diabatic heat-

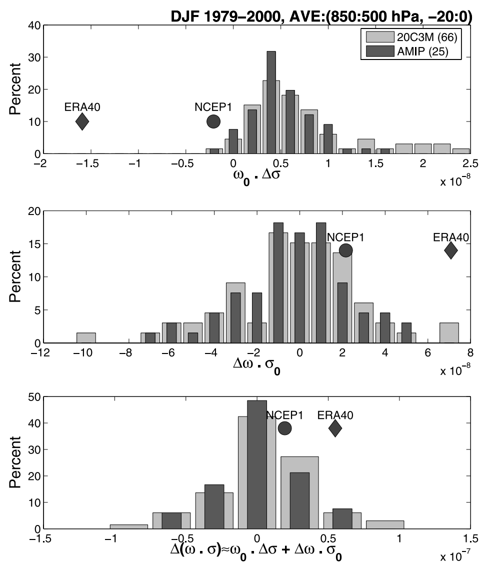

Figure 5. PDFs of the terms of the diabatic heating equation (see text for details) from 25 AMIP and 66 20C3M simulations for DJF 1979–2000, averaged over an appropriate region of the upward branch of the Hadley cell. Upper panel: static stability variation; middle panel: pressure vertical velocity variation; lower panel: total variation of diabatic heating proxy. Superposed are the values for the NCEP/NCAR and ERA40 reanalyses.

ing which is balanced by an increase in the Hadley cell intensity, and a weaker static stability.

5. Summary and Discussion

[13] Comparison of changes in the Hadley circulation and the thermodynamic structure of the tropical atmosphere reveals some large discrepancies, which are summarized as follows:

[14] • The majority of 94 model simulations show a decrease, or no increase of their DJF Hadley cell strength, opposite to the significant increase in the reanalyses, particularly in ERA40 over the period 1979–2000.

[15] • Almost all model simulations show an increase of the tropical mid-tropospheric static stability for DJF 1979–2000, consistent with the adjustment of the moist adiabat to a warming surface. Again this is opposite in sign to the significant decrease in the static stability in reanalyses due to a cooling of the upper mid-troposphere. ERA40 has a larger decrease in static stability than NCEP/NCAR.

[16] • An analysis of the energy balance shows that the models and reanalyses have a fundamentally different balance between diabatic heating, circulation and thermodynamic structure over the period 1979–2000.

[17] While all the models show consistent response to surface warming with warming aloft and increased stability, because the dependence of their thermal structure on parameterizations there is the possibility that the models are not entirely realistic. On the other hand, the reanalyses are continuously constrained by the assimilation of radiosonde profiles in the tropics, among other observed data sets. These radiosonde profiles show a cooling in the upper tropical troposphere [*Santer et al.*, 2005] which is apparently present in the reanalyses. With this reduced static stability, the Hadley circulation speeds up to accomplish the required heat transport, hence the increase in Hadley cell intensity. These observational temperature trends are far from certain, since there are significant errors and biases in radiosonde and satellite data sets as well as in the reanalyses [*Mears and Wentz*, 2005; *Santer et al.*, 1999, 2005; *Sherwood et al.*, 2005].

[18] In conclusion, the results of this study suggest that state-of-the-art simulations appear to handle tropical dynamics and thermodynamics in a different manner than observationally-constrained reanalyses data sets over recent decades. The issue of observed as well as assimilated upper level tropical temperature trends is central to the low-frequency behavior of the Hadley circulation intensity. Thus, because of uncertainties in the actual observations of tropospheric temperature [*Santer et al.*, 2005], how observations are assimilated into the reanalyses, and potential biases and errors in the models, it is unclear what is the true long-term behavior of the Hadley cell. A more comprehensive picture of the tropical circulation and thermodynamic structure may emerge as additional, more direct measures of the circulation become available and as trends in tropical temperature profiles are reconciled [*Lanzante et al.*, 2003; *Mears and Wentz*, 2005; *Santer et al.*, 2005; *Sherwood et al.*, 2005].

[19] **Acknowledgments.** We acknowledge the international modeling groups 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 Modelling (WGCM) and their Coupled Model Intercomparison Project (CMIP) and Climate Simulation Panel for organizing the model data 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. We thank Ben Santer for his valuable review suggestions. This work was funded by NASA Grant NNG04GM67G.

References

Kim, H. K., and S. Lee (2001), Hadley cell dynamics in a primitive equation model. part I: Axisymmetric flow, *J. Atmos. Sci.*, *58*, 2845–2858.

Knutson, T. R., and S. Manabe (1995), Time-mean response over the tropical Pacific to increased CO_2 in a coupled ocean-atmosphere model, *J. Clim.*, *8*, 2181–2199.

Lanzante, J. R., et al. (2003), Temporal homogenization of monthly radiosonde temperature data. part II: Trends, sensitivities, and MSU comparison, *J. Clim.*, *16*, 241–262.

Mears, C. A., and F. J. Wentz (2005), The effect of diurnal correction on satellite-derived lower tropospheric temperature, *Science*, *309*(5740), 1548–1551.

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.

Quan, X.-W., et al. (2004), Change of the tropical Hadley cell since 1950, in *The Hadley Circulation: Past, Present, and Future*, edited by H. F. Diaz and R. S. Bradley, pp. 85–120, Cambridge Univ. Press, New York.

Rind, D., et al. (1992), Climate change and the middle atmosphere. 2. The impact of volcanic aerosols, *J. Clim.*, *5*, 189–208.

Santer, B. D., et al. (1999), Uncertainties in observationally based estimates of temperature change in the free atmosphere, *J. Geophys. Res.*, *104*, 6305–6333.

Santer, B. D., et al. (2005), Amplification of surface temperature trends and variability in the tropical atmosphere, *Science*, *309*(5740), 1551–1556.

Santer, B. D., et al. (2006), How well can the observed vertical temperature changes be reconciled with our understanding of the causes of these changes?, in *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences—A Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research*, edited by T. R. Karl et al., Natl. Clim. Data Cent., NOAA, Asheville, N. C., in press.

Sherwood, S., et al. (2005), Radiosonde daytime biases and late-20th century warming, *Science*, *309*(5740), 1556–1559.

Tanaka, H. L., et al. (2004), Trend and interannual variability of Walker, monsoon and Hadley circulations defined by velocity potential in the upper troposphere, *Tellus, Ser. A*, *56*, 250–269.

A. Clement and C. M. Mitas, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL 33149, USA. (cmitas@rsmas. miami.edu)