Has the Hadley cell been strengthening in recent decades?

Christos M. Mitas and Amy Clement

Division of Meteorology and Physical Oceanography, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, Florida, USA

Received 15 October 2004; revised 14 December 2004; accepted 12 January 2005; published 8 February 2005.

[1] The intensity and structure of the Northern Hemisphere DJF Hadley cell as depicted in various commonly used data sets are examined. We find that the NCEP/NCAR and ECMWF reanalyses show a statistically significant intensification of their Hadley circulation throughout their periods. In marked contrast the NCEP-DOE reanalysis does not show any discernible trend over its period. Furthermore, the Hadley cell structure differs substantially from the other two reanalyses. We also examine a data set of global rawinsonde observations in which the Hadley cell shows no intensification. Finally, we investigate the Hadley cell simulated by an atmospheric GCM. The ensemble mean shows a statistically significant intensification, though it is smaller in magnitude than the reanalyses. We conclude that the two major reanalyses appear to be in agreement on the strengthening of the Hadley cell in recent decades. However, discrepancies among data sets do raise questions about the robustness of this strengthening.
Citation: 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.

1. Introduction

[2] Recent satellite observations provide evidence of decadal variability of the radiation budget of the tropical atmosphere [*Chen et al.*, 2002; *Wielicki et al.*, 2002]. The observations suggest an increase of the long-wave radiation emitted by Earth in the order of $\sim$5 W m^{-2}, and at the same time a reduction of the reflected short-wave radiation by less than $\sim$2 W m^{-2} for the period 1985–2000. *Chen et al.* [2002] have suggested that these trends are related to an intensification of the tropical atmospheric circulation, and in particular the Hadley cell. They argue that increased upward motions due to stronger tropical circulation would increase the cloudiness and upper level humidity in the equatorial belt, and decrease cloudiness in the subtropics. Such changes would directly affect the radiation budget of the tropics in a way that is consistent with the satellite observations. Is there evidence that the Hadley cell has, in fact, increased in strength over that time period?

[3] Some attention has recently been given to the long-term variability of the Northern Hemisphere December-January-February (DJF) tropical Hadley cell. *Quan et al.* [2004] have investigated the changes evident in the NCEP/NCAR reanalysis (version 1) from the nineteen-fifties. They found an intensification of the cell, and attributed this trend to both the warming of the tropical ocean and to increased El Niño frequency and amplitude after 1976. *Tanaka et al.* [2004] have also attempted to quantify recent changes in the boreal Hadley cell using the maximum velocity potential of the upper troposphere. They also used version 1 of the NCEP/NCAR reanalysis data and found a clear strengthening trend.

[4] Here we wish to investigate whether such trends are robust. To do so, we analyze the low-frequency variability of the Hadley cell in multiple commonly used data sets. We also address the complementary question: Is SST variability the principal cause of the Hadley cell long-term tendencies? This question is addressed by examining AMIP simulations with the CAM AGCM model.

2. Data and Analysis

2.1. Data Sets

[5] The data sets used in this study include the following three reanalyses products:

- NCEP/NCAR reanalysis (NCEP1, 1948–2003 [*Kalnay et al.*, 1996])
- NCEP-DOE AMIP-II reanalysis (NCEP2, 1979–2003 [*Kanamitsu et al.*, 2002])
- ECMWF 40-year reanalysis project (ERA40, 1958–2001)

[6] We also use a data set of rawinsonde data that have been objectively analyzed to produce the global gridded data set known as the Geophysical Fluid Dynamics Laboratory Atmospheric Circulation Tape Library (OORT, 1959–1989). Detailed descriptions of this data set are given by *Oort and Yienger* [1996] and *Waliser et al.* [1999].

[7] In addition, one set of model simulations is considered. Namely the 15-member ensemble mean of the Community Atmospheric Model (CAM v2.0.1) runs, forced by AMIP-like SSTs (CAM2-ENS). Because this model is forced only by observed SST changes, the atmospheric response can be directly attributed to the SST variability once internal dynamics have been accounted for by averaging over the ensemble.

[8] All the data sets used in this paper are global and gridded. A summary is provided in Table 1. In addition to these principal data sets we use the extended Kaplan SST analysis [*Kaplan et al.*, 1998] to define the ENSO signal by using SSTs over the Niño 3.4 region.

2.2. Methodology

[9] The Hadley circulation is the primary feature of the tropical atmospheric general circulation [*Oort and Yienger*, 1996; *Peixoto and Oort*, 1992]. It extends roughly from 15° in the summer hemisphere to 30° in the winter hemisphere. It is defined by equator-ward flow close to the surface in the tropics, an upward branch in the ITCZ, return pole-ward flow at the upper troposphere, and, to close the circuit, a

0094-8276/05/2004GL021765

Table 1. The Data Sets That are Examined in Terms of Their Hadley Cell Characteristics

Name	Description	Time Period
NCEP1	NCEP/NCAR reanalysis I	1948–2003
NCEP2	NCEP-DOE reanalysis II	1979–2003
ERA40	ECMWF reanalysis	1958–2001
OORT	Objectively analyzed rawinsonde network data.	1959–1989
CAM2-ENS	15-member ensemble of CAM simulations forced by SSTs	1950–2000

downward subsiding branch at the subtropics. The center of the circulation is located in the upper troposphere (∼450 hPa) and fairly close to the equator (∼10° in the winter hemisphere). In this study we focus on the Northern Hemisphere winter cell (DJF) since previous studies have suggested a strengthening only in that season [*Quan et al.*, 2004; *Tanaka et al.*, 2004]. The same analysis techniques used here have been applied to the Southern Hemisphere winter cell (JJA). However, we find no clear signal in the long-term behavior of the cell in any of the data sets, and therefore do not discuss it here.

[10] Figure 1 displays the zonal mean stream function for the DJF Hadley cell in the five data sets that we use in this study over their respective time periods. This two-dimensional stream function ($\psi(\phi, p)$ where ϕ is the latitude and p the pressure) is computed by vertically integrating the monthly meridional wind [*Oort and Yienger*, 1996; *Peixoto and Oort*, 1992; *Waliser et al.*, 1999]. The first order Hadley cell features are present in all climatologies, although with some notable differences. The OORT data set shows an anomalous penetration of the winter Hadley cell in the Southern Hemisphere, which *Waliser et al.* [1999] attributed to inadequate sampling in the Southern Hemisphere. Another important difference is the low circulation center (∼800 hPa) in NCEP2, which is in contrast to NCEP1 and ERA40 where the center of the circulation is in the upper troposphere (∼450 hPa). The intensity of the cell ranges from 16–21 $\times$ 10^{10} kg s^{-1} among the observational/reanalyzed data sets (see Table 2). The model simulations capture the same main features of the Hadley cell and the intensity falls within the range of the observational/reanalyzed data sets.

[11] To investigate the temporal variability of the intensity of the Hadley cell we use the Hadley cell strength index established by *Oort and Yienger* [1996]. For the Northern Hemisphere, it is defined as the maximum value in the tropics (0°–30°N) of the stream function of the meridional overturning circulation averaged over boreal winter (DJF). To address whether the signal of the Hadley cell strength indices originates from any changes in ENSO, we remove the ENSO signal by regressing on the Niño 3.4 index and keeping the regression residuals.

3. Results

[12] The Hadley cell strength index for all the data sets is shown in Figure 2. First we note that the ENSO signal in the zonal mean Hadley cell is not large since the residuals are very similar to the index itself. This is in contrast to the conclusion of *Quan et al.* [2004] that the strengthening of the Hadley cell shown in the NCEP/NCAR reanalysis in the last decades may be partially attributed to increased frequency and amplitude of El Niño. The correlations between the Hadley cell strength index and the Niño 3.4 SST index are shown in Table 2. *Oort and Yienger* [1996] found similar values using the OORT data set and concluded that during El Niño events the Hadley cell is stronger, though it should be noted that the correlation in that data set is fairly small. We also note here that there is an extremely large range in the value of this correlation among the different data sets, which raises questions about the robustness of the connection between the Hadley cell and ENSO. Moreover, after removing the ENSO signal from the Hadley cell index, we find that there is no significant effect on the long-term trends.

[13] The NCEP1 and ERA40 reanalyses exhibit a strengthening trend throughout their period, 7.5 $\times$ 10^8 kg s^{-1}/year and 21.3 $\times$ 10^8 kg s^{-1}/year, respectively, which passes the *t*-test at virtually all levels of significance. *Tanaka et al.* [2004] reported the same result for NCEP1, but used a different measure of the Hadley cell strength, the maximum of the zonal mean of the velocity potential at 200 hPa. NCEP2 has a trend of 1.2 $\times$ 10^8 kg s^{-1}/year with a low significance level. The OORT data set also shows a very small, positive upward trend of 0.3 $\times$ 10^8 kg s^{-1}/year, with

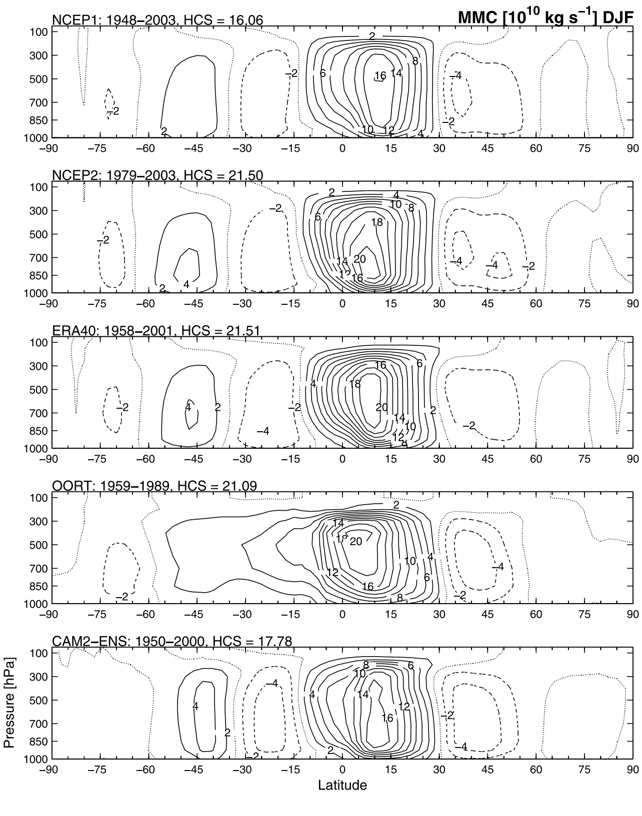

Figure 1. DJF climatology of the stream function of the mean meridional circulation for the five data sets described in Table 1. The Hadley cell strength index is also shown in units of 10^{10} kg s^{-1}.

Table 2. Various Hadley Cell Features of the Six Data Sets Described in Table 1: Maximum Value of the DJF Climatological Mean Stream Function (See Also Figure 1) in Column 1; Correlation Between the Hadley Cell Strength Index (HCS) and the SSTs at the Niño 3.4 Region Over the Period of Each Data Set in Column 2; Linear Trend of the Hadley Cell Strength (and Its Significance Level) in Column 3 Over Each Data Set Period; for NCEP1 and ERA40 the Trend is Also Shown for the OORT (1959–1989) and NCEP2 (1979–2003) Periods (See Also Figure 2)

Data Set	Maximum Stream Function [10^{10} kg s^{-1}]	Correlation HCS Vs. Niño3.4 [%]	Trend [10^8 kg s^{-1}/year] (Significance Level [%])
NCEP1	16.06	26.0	7.47 (>99)
			8.29 (>99) [over OORT]
			10.7 (>99) [over NCEP2]
NCEP2	21.50	57.7	1.23 (42.2)
ERA40	21.51	7.9	21.26 (>99)
			18.5 (>99) [over OORT]
			29.6 (>99) [over NCEP2]
OORT	21.09	24.7	0.29 (11.9)
CAM2-ENS	17.78	73.4	2.07 (86.72)

negligible statistical significance. NCEP1 and ERA40 also show significant linear trends over the periods of the OORT and NCEP2 data sets, (1959–1989 and 1979–2003, respectively; see Table 2). Finally, the CAM2-ENS model shows small, positive trends throughout its period of 2.0×10^8 kg s^{-1}/year and considerable significance level. Hence, CAM2-ENS appears to show the same overall tendency as the two reanalyses that show significant upward trends, albeit with an almost tenfold reduction in value. For an overview of these trends and significance levels, see Table 2.

[14] In order to determine whether the index shown in Figure 2 captures the low-frequency variability of the Hadley cell, we performed an EOF analysis on the three data sets that show a trend at a significance level above 80%

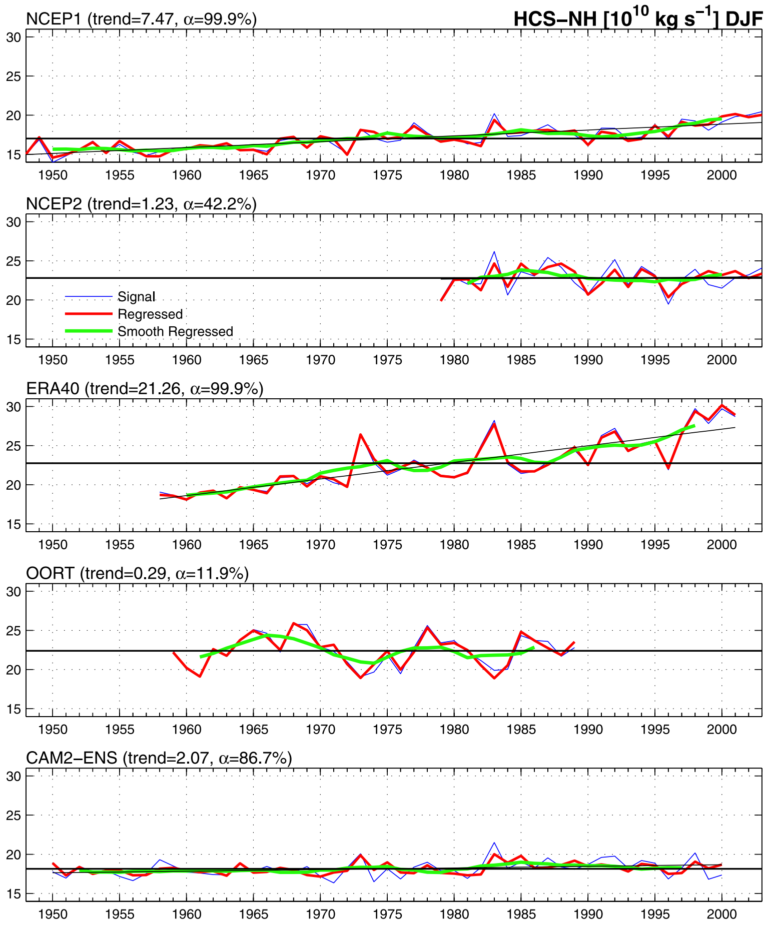

Figure 2. Northern Hemisphere, DJF Hadley cell strength index for the different data sets described in Table 1. Displayed also are the residuals of the regression to Niño 3.4 SST index (red line) and its 6-point running mean (green line). The time mean of the index is also drawn (constant heavy black line) along with its linear trend (thin black line). The linear trend over the whole period (in units of 10^8 kg s^{-1}/year) and its significance level are also shown.

(NCEP1, ERA40 and CAM2-ENS). The first EOF captures a significant fraction of the variance for all data sets, and shows that there is a general intensification of the Hadley cell over most of its area. Moreover, the principal components show a clear upward trend (not shown) that is consistent with the time series of the index shown in Figure 2. Thus we conclude that, in the data sets that have a significant strengthening trend, there is a consistent spatial structure of change that is captured by the Hadley cell index. We note, however, that this is only true for these three data sets, while in the rest there is no such signal (not shown).

4. Discussion and Conclusions

[15] We consider the Hadley cell structure and intensity in three reanalyses data sets, a rawinsonde data set and one model ensemble which is forced by observed SSTs. Our main objective is to establish common features and highlight differences among the reanalyses in terms of the Hadley cell decadal variability. The results can be summarized as follows:

[16] • Two of the major reanalyses projects, NCEP1 and ERA40, show an upward tendency of the Hadley cell strength over the last several decades. This is consistent with the observed satellite radiation measurements. The fact that there has been an increase in the Hadley cell over the entire period implies that it is not an artifact of the inclusion of the satellite data in the post-1979 period because the trend exists both before and after 1979. This is in contrast to trends in temperature and humidity in the ERA analysis which have been attributed to the inclusion of satellite data by *Bengtsson et al.* [2004].

[17] • This upward trend cannot be attributed to increasing ENSO frequency, since it persists even when the ENSO signal (at least the part that is linearly dependent on Niño 3.4 SSTs) has been removed. This is in contrast to the partial attribution by *Quan et al.* [2004] of the trend in DJF Hadley intensity on increased El Niño frequency and amplitude.

[18] • The structure and intensity of the Hadley cell of NCEP1 and ERA40 are fairly similar to each other in terms of their climatology (see Figure 1).

[19] • The NCEP2 reanalysis has considerable dissimilarities with both NCEP1 and ERA40. This is somewhat surprising, since errors that were in the NCEP1 reanalyses were fixed to produce NCEP2. One of the main differences between NCEP1 and NCEP 2 is the 50% reduction of the albedo over the tropical oceans from $\sim$0.15 to $\sim$0.065 [*Kanamitsu et al.*, 2002]. Perhaps this change influences the vertical structure of the meridional wind, hence explaining the lower circulation center in NCEP2. However, this would have to come about indirectly through a highly nontrivial set of processes, so it is an open question as to why NCEP1 and NCEP2 show different low-frequency behavior of the Hadley cell.

[20] • The OORT data set shows no discernible long-term trend. While the time period for this data set is shorter, when the trends in NCEP1 and ERA are computed over this same interval, there is still a significant trend in those data sets (Table 2). Thus, the discrepancy does not arise because of different temporal coverage. On the other hand, there may be some differences that arise because of spatial coverage. *Waliser et al.* [1999] showed that the difference in meridional stream function between OORT and NCEP can be related to the sampling (see Figure 1). Since OORT is comprised of rawinsondes it lacks information over the oceans, where some of the strengthening signal might originate, as suggested by the CAM-ENS results, which could explain the absence of a strengthening.

[21] • The ensemble of the CAM simulations exhibits a small but nonetheless discernible trend in its Hadley cell strength index over its full period, including the last fifteen years. The significance level of its trend is fairly high ($\sim$87%). This may be taken as evidence that an AGCM forced by the observed SSTs is capable of producing an intensification of the Hadley cell, if only a weak one.

[22] In summary, there appears to be agreement that the Hadley cell has been strengthening over the past several decades among the two state-of-the-art reanalyses of the major data centers, NCEP/NCAR and ECMWF, and the atmospheric GCM forced with observed SSTs. However, because the signal is not consistent across all of the commonly used data sets, there are still some questions about the robustness of this result that should be considered when interpreting long-term trends in the Hadley cell.

[23] One potential source of the discrepancies is the cloud parameterization and convective schemes used in the reanalyses models and the AGCMs. The upward branches of the Hadley cell are particularly affected by these highly parameterized model components. Experiments with AGCMs and coupled GCMs can be constructed to test the sensitivity of the Hadley cell to parameterization for example by swapping out different schemes or altering parameter values (i.e., as by *Renno et al.* [1994]). In addition, the 'super parameterization' methodology of *Randall et al.* [2003] would be a useful approach to evaluate the sensitivity of the large-scale circulation to sub-grid scale processes.

[24] The sparse observational network in the tropical latitudes is also one of the principal culprits of our inadequate picture of the Hadley cell in Earth's atmosphere [*Waliser et al.*, 1999]. A denser surface observational network of tropical meridional winds would help provide a clearer picture of the Hadley cell and its long-term variability. However, there are obvious limitations to the development of a consistent, long-term observational network over the tropics where most of the area is ocean. On the other hand, *Velden et al.* [1997] have developed algorithms to remotely sense upper-level winds in the tropics, and have suggested that such a data set could be applied to climate studies. Exploitation of those data may help to provide a more consistent picture of the Hadley cell and its temporal behavior.

[25] In conclusion, the results of this study indicate that the features of the Hadley cell, in particular its long-term temporal behavior, must be refined. Previous studies have suggested that changes in the Hadley cell may be crucial for various climatic feedbacks, in particular marine stratus clouds in the subtropics [*Clement and Seager*, 1999; *Miller*, 1997; A. Clement and B. J. Soden, The sensitivity of the tropical mean radiation budget, submitted to *Journal of Climate*, 2004], and the global impact in the atmospheric aerosols distribution [*Meehl et al.*, 2003; *Miller and Tegen*,

1999]. Without the ability to consistently measure the intensity and monitor the temporal behavior of the Hadley cell, its role in climate change will remain elusive.

[26] **Acknowledgments.** The authors are grateful to Brian Soden for his input. We also thank Adam Phillips of the Climate and Global Dynamics Division at NCAR for providing the CAM2 ensemble data. This work was funded by NASA Grant # NNG04GM67G.

References

Bengtsson, L., S. Hagemann, and K. I. Hodges (2004), Can climate trends be calculated from reanalysis data?, *J. Geophys. Res.*, *109*, D11111, doi:10.1029/2004JD004536.

Chen, J. Y., B. E. Carlson, and A. D. Del Genio (2002), Evidence for strengthening of the tropical general circulation in the 1990s, *Science*, *295*(5556), 838–841.

Clement, A., and R. Seager (1999), Climate and the tropical oceans, *J. Clim.*, *12*(12), 3383–3401.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*(3), 437–471.

Kanamitsu, M., W. Ebisuzaki, J. Woollen, S. K. Yang, J. J. Hnilo, M. Fiorino, and G. L. Potter (2002), NCEP-DOE AMIP-II reanalysis (R-2), *Bull. Am. Meteorol. Soc.*, *83*(11), 1631–1643.

Kaplan, A., M. A. Cane, Y. Kushnir, A. C. Clement, M. B. Blumenthal, and B. Rajagopalan (1998), Analyses of global sea surface temperature 1856–1991, *J. Geophys. Res.*, *103*(C9), 18,567–18,589.

Meehl, G. A., W. M. Washington, T. M. L. Wigley, J. M. Arblaster, and A. Dai (2003), Solar and greenhouse gas forcing and climate response in the twentieth century, *J. Clim.*, *16*(3), 426–444.

Miller, R. L. (1997), Tropical thermostats and low cloud cover, *J. Clim.*, *10*(3), 409–440.

Miller, R. L., and I. Tegen (1999), Radiative forcing of a tropical direct circulation by soil dust aerosols, *J. Atmos. Sci.*, *56*(14), 2403–2433.

Oort, A. H., and J. J. Yienger (1996), Observed interannual variability in the Hadley circulation and its connection to ENSO, *J. Clim.*, *9*(11), 2751–2767.

Peixoto, J. P., and A. H. Oort (1992), *Physics of Climate*, 520 pp., Am. Inst. of Phys., New York.

Quan, X.-W., H. F. Diaz, and M. P. Hoerling (2004), Change in the tropical Hadley cell since 1950, in *The Hadley Circulation: Past, Present, and Future*, edited by H. F. Diaz and R. S. Bradley, Cambridge Univ. Press, New York.

Randall, D., M. Khairoutdinov, A. Arakawa, and W. Grabowski (2003), Breaking the cloud parameterization deadlock, *Bull. Am. Meteorol. Soc.*, *84*(11), 1547–1564.

Renno, N. O., K. A. Emanuel, and P. H. Stone (1994), Radiative-Convective model with an explicit hydrologic-cycle: 1. Formulation and sensitivity to model parameters, *J. Geophys. Res.*, *99*(D7), 14,429–14,441.

Tanaka, H. L., N. Ishizaki, and A. Kitoh (2004), Trend and interannual variability of Walker, monsoon and Hadley circulations defined by velocity potential in the upper troposphere, *Tellus, Ser. A*, *56*(3), 250–269.

Velden, C. S., C. M. Hayden, S. J. Nieman, W. P. Menzel, S. Wanzong, and J. S. Goerss (1997), Upper-tropospheric winds derived from geostationary satellite water vapor observations, *B. Am. Meteorol. Soc.*, *78*(2), 173–195.

Waliser, D. E., Z. Shi, J. R. Lanzante, and A. H. Oort (1999), The Hadley circulation: Assessing NCEP/NCAR reanalysis and sparse in situ estimates, *Clim. Dynam.*, *15*(10), 719–735.

Wielicki, B. A., T. M. Wong, R. P. Allan, A. Slingo, J. T. Kiehl, B. J. Soden, C. T. Gordon, A. J. Miller, S. K. Yang, D. A. Randall, F. Robertson, J. Susskind, and H. Jacobowitz (2002), Evidence for large decadal variability in the tropical mean radiative energy budget, *Science*, *295*(5556), 841–844.

A. Clement and C. M. Mitas, Division of Meteorology and Physical Oceanography, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, 4600 Rickenbacker Causeway, Miami, FL 33149, USA. (cmitas@rsmas.miami.edu)