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Climate change during 1985–1999: Cloud interactions determined from satellite measurements

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[1] We have extended two recent studies that present evidence for significant decadal variability in the top-of-atmosphere (TOA) tropical radiative energy budget by combining satellite measurements of the TOA energy budget and cloud cover with measurements of the Earth's surface temperature. The domain studied is from 40°S to 40°N. As in the prior studies, which were restricted to lower latitudes, there is a significant increase in the TOA outgoing longwave radiation during the period 1985 to 1999 together with an increase in solar (shortwave) radiation absorbed by the climate system. It is suggested that these changes are related to an observed reduction in cloud cover. *INDEX TERMS:* 3309 Meteorology and Atmospheric Dynamics: Climatology (1620); 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 1610 Global Change: Atmosphere (0315, 0325). **Citation:** Cess, R. D., and P. M. Udelhofen, Climate change during 1985–1999: Cloud interactions determined from satellite measurements, *Geophys. Res. Lett.*, *30*(1), 1019, doi:10.1029/2002GL016128, 2003.

1. Introduction

[2] Two recent studies [*Wielicki et al.*, 2002a; *Chen et al.*, 2002] have presented evidence for substantial changes in the Earth's tropical radiation energy budget at the top-of-atmosphere (TOA) over a roughly two decade time period. *Wielicki et al.* suggest this is caused by changes in tropical mean cloudiness, which could be consistent with evidence presented by *Chen et al.* for a decadal strengthening of the tropical Hadley and Walker circulations. To better understand this phenomenon, we extend the interpretation of the TOA radiation budget beyond the tropics to include latitudes 40°S to 40°N, and then combine these data with measurements of surface temperature as well as with satellite measurements of cloud fraction. Moreover, to better understand the combined data sets, we first consider output from a coupled atmosphere-ocean climate model that incorporates increasing greenhouse gases.

2. Analysis

[3] Annual-mean outputs for the last 29 years of a long run (1870–1998) from the NCAR (National Center for Atmospheric Research) CCSM1 (Community Climate System Model, version 1) are shown in Figure 1 as anomalies relative to 1970. The model is a coupled atmosphere-ocean general circulation model that incorporates time-dependent increases in both greenhouse gases and sulfate aerosols [*Dai et al.*, 2001]. The surface-temperature anomaly, ΔT_S (Figure 1a), refers to global-mean surface temperature since we are interested in the response to global climate change, while the ASW and OLR anomalies (Figure 1b) are 40°S to 40°N means so as to be consistent with the satellite radiometric data. These were evaluated from the model's monthly-mean gridded output. The positive trend of ΔT_S is the result of increasing greenhouse gases within the model, whereas the negative trend of ΔASW has two causes. The clear-sky ΔASW (not shown) exhibits a very small negative trend that is due to the model's increasing sulfate aerosols. The presence of clouds within the model causes an enhancement of this negative trend, in proceeding from clear-sky to all-sky ΔASW, indicating the model possesses a modest negative SW cloud feedback.

[4] To better understand the mechanisms governing ΔOLR, it is useful to employ the greenhouse parameter [*Raval and Ramanathan*, 1989] $G = 1 - (OLR/\sigma T_S^4)$, where σ is the Stefan-Boltzmann constant. The averaged T_S^4 was determined from the monthly-mean T_S^4 at each model grid point and then averaged over space and time to produce 40°S to 40°N annual means, and note that $OLR/\sigma T_S^4$ is evaluated as the ratio of the domain-averaged annual means. An increase in G denotes an increase in the greenhouse effect and vice versa. The positive ΔG trend shown in Figure 1c is mainly due to the prescribed increase in greenhouse gases within the model, in addition to the increase in tropospheric water vapor caused by the warming climate (positive water vapor feedback, which implicitly includes lapse rate changes) that models exhibit [*Cess et al.*, 1990]. But this is moderated by the presence of clouds. The slope of the linear trend in Figure 1c is roughly 25% lower than that for clear skies (not shown), indicating a negative LW cloud feedback, caused by a cloud-induced reduction in G, and this is of greater magnitude than the negative SW cloud feedback just discussed.

[5] To summarize the above, the increase in G (Figure 1c) produces a direct reduction in OLR (forcing), while the increase in surface temperature correspondingly increases OLR (response). The net effect, for the present model simulation, is the negative OLR trend shown in Figure 1b. But the latter (response) process could be governed by ΔASW. If the ASW trend in Figure 1b were positive, resulting in a greater increase in T_S, one might expect a positive trend in OLR caused by the climate-induced increase in OLR overriding the G-induced decrease in OLR.

[6] We next analyze data in much the same way as the CCSM1 outputs of Figure 1, except with restriction to the 15-year period 1985–1999 that coincides with the satellite radiometric data that we employ, and with anomalies referenced to 1985. Shown in Figure 2a is the change in global-

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[1] Deceased 17 May 2002.

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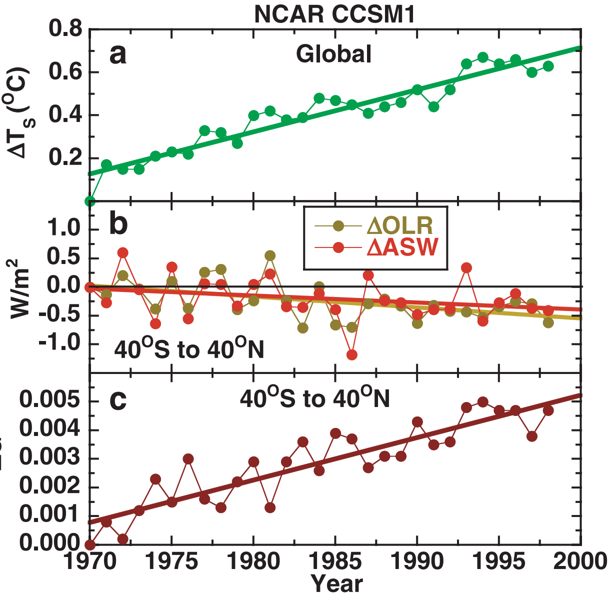

Figure 1. (a) Change in the global-mean surface temperature (ΔT_S), referenced to 1970, for the last 29 years of an 1870–1998 simulation with the NCAR CCM1. The straight line is the linear trend. (b) The same as (a) but for but for ΔOLR and ΔASW and averaged from 40°S to 40°N. (c) The same as (b) but for the change in the greenhouse parameter (ΔG).

mean surface temperature [*Jones et al.*, 2001] and, as emphasized by *Wielicki et al.* [2002a], this period contained not only two significant El Niños, but also the eruption of Mt. Pinatubo. As in *Wielicki et al.* [2002a], we employed 10° × 10° monthly-mean gridded data determined from measurements made by the Earth Radiation Budget Experiment (ERBE) wide-field-of-view (WFOV) instruments on the Earth Radiation Budget Satellite (ERBS) for the 1985–1999 period. *Chen et al.* [2002] likewise employed ERBE WFOV measurements, but they used an earlier data set for the period 1985–1995. To minimize sampling errors associated with the 72 day period for the ERBS orbit to precess through 24 hours of local time sampling [*Trenberth*, 2002; *Wielicki et al.*, 2002b], we restrict attention solely to annual means.

[7] There are temporal data gaps in the 15-year ERBS record. The first occurred when the instrument was powered down for 4 months in July to November 1993 [*Wielicki et al.*, 2002b]. When ERBS resumed taking data in December 1993, the spacecraft could not supply sufficient power for about 6 days out of every 36 days. With improved power management, and starting in mid 1995, the days of missing data were progressively reduced until there were no missing days after 5 February 1999. We filled missing data by first constructing a monthly-mean climatology, for each 10° zonal band, for the years 1985–1989. Anomalies were then taken to be the departures from that climatology, were smoothed with a 12-month filter, and were linearly interpolated to fill the data gaps and reconverted to absolute values using the climatology.

[8] The ΔASW and ΔOLR results, for 40°S to 40°N, are summarized in Figure 2b and, like the tropical (20°S to 20°N) anomalies demonstrated by *Wielicki et al.* [2002a], they are substantial and indicate that such anomalies extend well beyond the tropics. Figure 2b is consistent with the suggestion that a substantial OLR anomaly might be accompanied by a comparable ASW anomaly. This consistency could, however, be a measurement artifact, since OLR and ASW were not determined from independent measurements. The ERBS WFOV instruments consist of two active cavity radiometers, one which is a filtered instrument that measures TOA reflected SW radiation, while the other is unfiltered and thus measures the sum of the reflected SW and emitted LW. The emitted LW is determined by subtracting the measurement of the filtered instrument from that of the unfiltered instrument. The filter, however, is known to degrade, and if this degradation had been underestimated, the result could be an underestimate of the reflected SW, thus overestimating ASW and, when the two instrument measurements are differenced, in turn resulting in an overestimate of OLR. *Wielicki et al.* [2002a], however, have demonstrated consistency with other measurements, and we next reiterate that point.

[9] Compared in Figure 2c are the ΔASW from Figure 2b to that determined from the SW scanner for the 5-yr

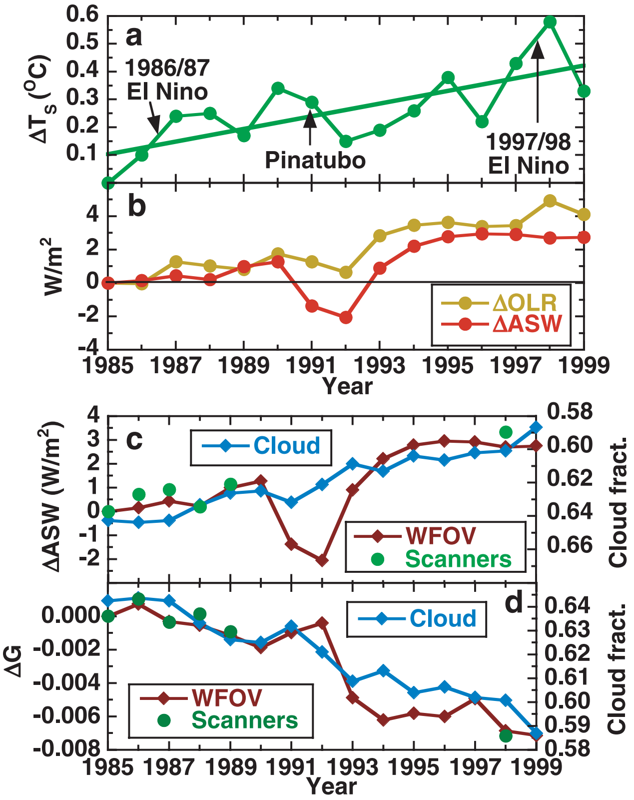

Figure 2. (a) Change in the global-mean surface temperature (ΔT_S), for the period 1985–1999 and referenced to 1985, from *Jones et al.* [2001]. (b) The anomalies ΔOLR and ΔASW, for the period 1985 to 1999 and referenced to 1985, as determined from measurements made by the ERBE WFOV instruments. (c) The ΔASW results from (b) from the ERBE WFOV measurements compared to those determined from the ERBE (1985–1889) and CERES (1998) scanner measurements, in addition to the ISCCP cloud cover fraction (note the reversed scale). (d) The same as (c) but for ΔG, and here the cloud-fraction scale in not reversed.

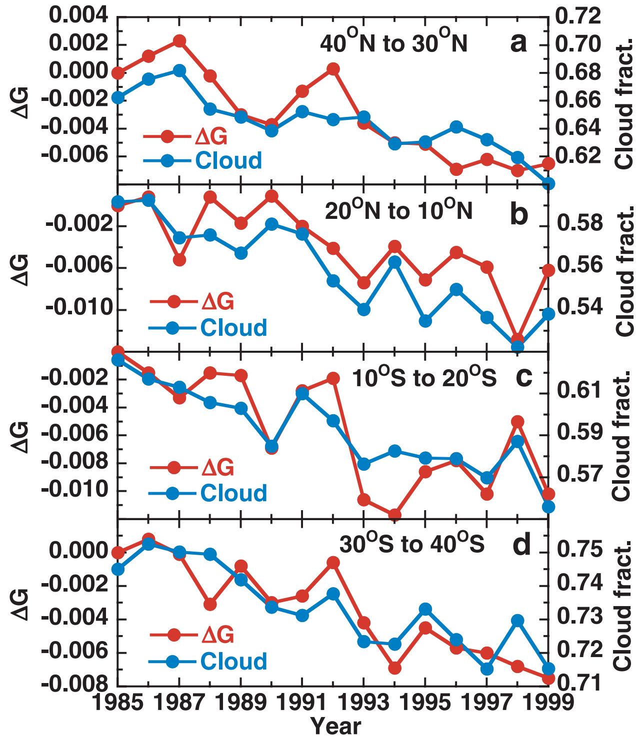

Figure 3. (a) ΔG determined from ERBE WFOV measurements and ISCCP cloud fraction, both averaged from 40°N to 30°N. (b) The same as (a) but for 20°N to 10°N. (c) The same as (a) but for 10°S to 20°S. (d) The same as (a) but for 30°S to 40°S.

period (1985–1989) from ERBE and for the first 8 months of 1998 from the Clouds and the Earth's Radiant Energy System (CERES) SW scanner on the Tropical Rainfall Measuring Mission (TRMM) Satellite. These data, and their consistency and accuracy, are discussed by *Cess et al.* [2001]. Since only 8 months of CERES/TRMM scanner data are available, that data, and the ERBE scanner data, have been averaged over the first 8 months of each year. The agreement of the ERBE/CERES scanner ΔASW to that determined from the ERBE SW WFOV instrument would argue against the positive ΔASW being an artifact of an underestimated filter degradation for the SW WFOV instrument. Also shown in Figure 2c are ISCCP (International Satellite Cloud Climatology Project) measurements of annual-mean total cloud fraction [*Rossow and Schiffer*, 1999], likewise averaged from 40°S to 40°N. Note the reverse scale for cloud fraction, and the negative trend of cloud fraction offers a plausible explanation for the positive ΔASW anomaly; the reduction in cloud cover reduces the reflected SW at the TOA and thus increases ASW. The ISCCP data show large decreases in cloud fraction at the east-west limbs of the geostationary satellites, which may or may not be real. But the negative trend in the 40°S to 40°N average remains even when these regions are removed when performing the average [Joel Norris, private communication, May 2002].

[10] The greenhouse-effect anomaly, ΔG, is shown in Figure 2d, again for 40°S to 40°N and again using both WFOV and ERBE/CERES scanner measurements. As for CCSM1, G was evaluated as $1 - (\mathrm{OLR}/\sigma T_S^4)$, with the annual-mean and domain-averaged T_S^4 determined from T_S^4 for individual 5° × 5° grids in the surface-temperature data set [*Jones et al.*, 2001]. Again there is excellent agreement between the WFOV and scanner measurements.

[11] Unlike CCSM1 (Figure 1c), the negative trend of G indicates that the atmospheric greenhouse effect is temporally decreasing, despite the fact that greenhouse gasses are increasing. To understand this, the following three factors can impact G:

1. An increase in greenhouse gases, which is occurring [*IPCC*, 2001] and by themselves would increase G.

2. An increase in tropospheric water vapor, and possibly also a change in lapse rate, associated with the increasing trend in T_S (Figure 2a). It is generally agreed that this increases the greenhouse effect and so acts as a positive climate feedback mechanism [*IPCC*, 2001; *Held and Soden*, 2000].

3. Clouds are a major contributor to the greenhouse effect and globally provide roughly 30 W/m^2 of LW warming to the climate system [*Ramanatthan et al.*, 1989]. So a change in cloudiness could have a major impact upon G. Either a decrease in cloud amount, or a reduction in cloud altitude resulting in warmer clouds that emit more LW radiation, would decrease G.

[12] *Wang et al.* [2002] have suggested that changes in cloud vertical structure could explain some of the OLR anomaly, although this would not explain the associated ASW anomaly. Conversely, changes in cloud fraction would seem, at least to first order, to explain both anomalies. Not only is the negative trend in cloud fraction consistent with the positive trend in ASW (Figure 2c), it is also consistent with the negative trend in G as demonstrated in Figure 2d where the scale for cloud fraction is not reversed. But for OLR the situation is possibly more complex than for ASW. A decrease in upper troposphere relative humidity (UTH) would also cause a reduction in G, and for the subtropics *Chen et al.* [2002] indicate a decrease in UTH associated with strengthening of the Hadley cell. But the strong correlation between ΔG and ΔASW, as demonstrated in

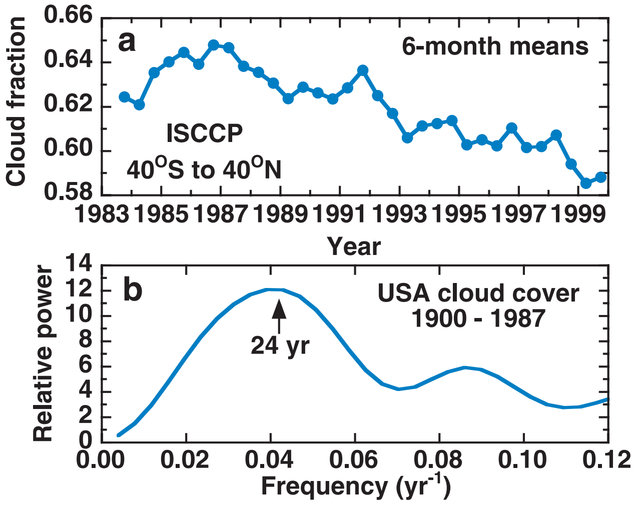

Figure 4. (a) Six-month means of the ISCCP cloud fraction data commencing in July 1983. (b) Power spectrum analysis of cloud fraction measurements for the continental United States for the period 1911 to 1987.

Figure 2e (note the reversed scale for ΔASW), and excluding the Pinatubo period, argues that changes in G and ASW appear to be linked in a manner that is largely explained by changes in cloud fraction.

[13] The correlation of G and cloud fraction is even more evident with respect to 10-degree zonal means, as demonstrated in Figure 3 which shows every other 10-degree latitude zone; much of the temporal structure of G is explained by cloud fraction.

[14] If changes in cloud fraction are the cause of the ASW and G anomalies, then the fundamental question is what is the cause of the cloud-fraction changes? One possibility, which we regard as somewhat unlikely, is that clouds are responding to the change in climate and thus providing substantial SW and LW cloud feedbacks. To put this in perspective, $\Delta\text{OLR} \approx 4\ \text{W/m}^{-2}$ in 1999 (Figure 2d), but removing the increase caused by ΔT_S, which should not be regarded as a contribution to the anomaly, produces $\Delta\text{OLR} \approx 3\ \text{W/m}^2$. On the other hand, we estimate that the radiative forcing due to increasing greenhouse gases from 1985 to 1999 at most produces a reduction in OLR of $\approx 1\text{W/m}^{-2}$, which brings us back to $\Delta\text{OLR} \approx 4\ \text{W/m}^2$. Finally, imbedded within this number is a probable negative contribution caused by increasing tropospheric water vapor, and possibly associated lapse rate changes, resulting from the warming climate. Thus for the "true anomaly" we would anticipate $\Delta\text{OLR} > 4\ \text{W/m}^2$. So if this LW cooling anomaly is the result of cloud feedback, then the $\approx 1\ \text{W/m}^{-2}$ forcing (warming) spawned a greater than $4\ \text{W/m}^2$ cooling and this would seem rather improbable. But even if this were the case, it does not mean the net cloud feedback would be strongly negative, because ΔASW would incorporate a positive SW cloud feedback. It is cautioned that the preceding numbers are purely illustrative and cannot serve as an estimate of cloud-climate interactions. Nor, because of interannual variability, can a single year be used for this purpose.

[15] There is evidence that the change in cloud fraction might be the result of natural variability on decadal time scales, consistent with suggestions by *Wielicki et al.* [2002a, 2002b] and *Chen et al.* [2002] within the context of internal unforced variability. The ISCCP cloud-fraction data commenced in July 1983, and to incorporate the 18 months of data prior to 1985, we have adopted six-month means as shown in Figure 4a. The early portion of this record provides a suggestion that the cloud fraction might be periodic with time. Surface observations of cloud cover over the continental United States are also indicative of a periodic behavior. The power spectrum shown in Figure 4b, based upon an average of measurements from 90 stations, shows a strong 24 year cycle in cloud cover. If this 24-year cycle were a global phenomenon, and depending upon how changes in cloud cover impact the radiation budget, one might anticipate a similar periodicity in surface temperature which is the case for central England [*Hameed and Wyant*, 1982; *Baliunas et al.*, 1997]. But if such a 24-year cycle in cloud cover is responsible for the observed ASW and G anomalies, the question remains whether this is an internal or externally forced variability.

3. Summary

[16] The primary conclusion of this study is that, for the 40°S to 40°N domain, there is evidence that the positive OLR and ASW anomalies during 1985–1999 are both related to a concurrent change in cloud cover. If the change in cloud cover is the result of natural variability acting over decadal time scales, this could considerably hamper efforts at detecting the radiative signature of future global warming, and this is an issue that needs to be clarified.

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