LETTERS

The Iris Hypothesis: A Negative or Positive Cloud Feedback?

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ABSTRACT

Using the Tropical Rainfall Measuring Mission (TRMM) satellite measurements over tropical oceans, this study evaluates the iris hypothesis recently proposed by Lindzen et al. that tropical upper-tropospheric anvils act as a strong negative feedback in the global climate system. The modeled radiative fluxes of Lindzen et al. are replaced by the Clouds and the Earth's Radiant Energy System (CERES) directly observed broadband radiation fields. The observations show that the clouds have much higher albedos and moderately larger longwave fluxes than those assumed by Lindzen et al. As a result, decreases in these clouds would cause a significant but weak positive feedback to the climate system, instead of providing a strong negative feedback.

1. Introduction

Lindzen et al. (2001), hereinafter LCH, recently reported that the ratio between upper-tropospheric anvil (UTA) and deep convective cloud (DCC) amounts over the tropical western Pacific oceanic area (30°N–30°S, 130°E–170°W) has a negative correlation with sea surface temperature (SST). Based on this observation, along with an estimate of the mean radiative properties of these clouds, they examined a simple radiative energy balance model (3.5-box greenhouse model) to infer that these tropical UTA clouds could provide a strong negative climate feedback for greenhouse gas–induced global warming (-0.45 to about -1.1 K K^{-1}). According to LCH, decreases in UTA amount with increased surface temperature would allow more thermal longwave (LW) radiation to emit to space and, therefore, would cool the climate system (i.e., IR iris effect). This feedback would be sufficiently strong potentially to negate many of the positive feedbacks, such as atmospheric water vapor, found in current climate models (e.g., Del Genio et al. 1991).

There are some key limitations to the iris study by LCH. First, the analysis of the ratio of UTA [220 K $<$ brightness temperature (Tb) $<$ 260 K] to DCC (Tb $<$ 220 K) areas is performed using geostationary satellite data over the western Pacific warm pool region. Results for this region are then assumed to apply across the entire Tropics. Second, the broadband albedos and LW fluxes for the three tropical regions (dry, clear moist, and cloudy moist) used in the simple climate model were based partially on model calculations and were only constrained to match mean global and tropical Earth Radiation Budget Experiment (ERBE) data (Barkstrom et al. 1989). Because there are many combinations of radiative properties that could meet the simple constraint of matching ERBE mean global and tropical values, this is a major limitation of the LCH results (also see the discussions of Fu et al. 2001, hereinafter FBH).

The current study uses the recent Tropical Rainfall Measuring Mission (TRMM; Simpson et al. 1996) satellite data across the entire tropical oceans to overcome both of these shortcomings and to test the iris hypothesis using more complete and rigorous tropical satellite observations. These observations are then used to drive the simple 3.5-box climate model defined in LCH.

2. Data analysis

All data analysis is for the 30°S–30°N tropical oceans as defined in LCH and includes the period from 1 January to 31 August 1998. The limited time is set by the Clouds and the Earth's Radiant Energy System (CERES) TRMM observing period. CERES instrument data (Wielicki et al. 1996) from the TRMM satellite provide the broadband top-of-atmosphere (TOA) solar reflected shortwave (SW) fluxes, albedos, and thermal emitted LW fluxes. The TRMM Visible and Infrared Scanner (VIRS) is a 2-km-field-of-view (FOV) narrowband imager with spectral channels at 0.65-, 1.61-, 3.75-, 10.8-, and 12-μm wavelengths. The VIRS 10.8-μm channel

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is used in this study because it is very similar to that on the geostationary satellite used by LCH. Data products used in this study include the CERES ERBE-like TOA fluxes (ES-8 edition 2) that are analyzed using the new CERES broadband data but with the traditional ERBE analysis methods (Barkstrom et al. 1989) and the CERES Single Scanner Footprint (SSF) edition-1 data product that merges the VIRS radiances and cloud properties with each CERES FOV. The SSF product was used to obtain the VIRS 10.8-μm channel radiances for the same 10-km nadir FOV as the CERES TOA fluxes. Both data products were obtained from the National Aeronautics and Space Administration (NASA) Langley Research Center's Atmospheric Sciences Data Center (http://eosweb.larc.nasa.gov/).

As in LCH, the tropical UTA and DCC areas are defined by the VIRS radiances with 220 K $<$ Tb $<$ 260 K and Tb $<$ 220 K, respectively. For both of these cloud types, a cloud-weighted SST is defined as in LCH, using the Reynolds SST analysis (Reynolds and Smith 1994) taken from the CERES SSF data product. The cloud fraction ratio of UTA to DCC areas, that is, Area(220 K $<$ Tb $<$ 260 K)/Area(Tb $<$ 220 K), is determined as a function of cloud-weighted SST. Although not shown, very similar results to LCH were found across the entire Tropics for the dependence of the cloud fraction ratio on cloud-weighted SST; namely, a decrease of roughly 20% per kelvin. We will not address the validity of assuming that current climate variations of the cloudiness with SST in the Tropics can mimic behavior accurately in a broad warming of the entire Tropics (or globe). This is beyond the scope of the current paper. Furthermore, Hartmann and Michelsen (2002) have shown that the relationship of cloud-weighted SST to the cloud fraction ratio results from changes in cloud amount over the coldest SST, far removed from the tropical deep convection whose UTA clouds LCH hypothesized are modulated by small SST variations. We only note that the TRMM data show similar changes of the cloudiness with SST but with a large reduction in the cloud amount. The total area of clouds with Tb $<$ 260 K was found to be only one-half that used in LCH (10% vs 22%). Note that the actual total area of clouds with Tb $<$ 260 K found by LCH ($\sim$15%; see Fig. 5a of LCH) is significantly smaller than the value (22%) they used in the 3.5-box climate analysis. The higher fractional coverage in LCH is caused by their use of the geostationary satellite viewing area dominated by the Pacific warm pool: a region with higher-than-average convective cloudiness. The use of 30°S–30°N over the warm pool in the LCH study includes the strongest portion of the Hadley cell and the ascent branch of Walker circulations but not the subsidence of Walker circulations. When restricted to the LCH region, we find that the cloud fraction increases to about 13%.

To test the LCH radiative properties, the data are separated into three tropical categories: cloudy-moist, clear-moist, and dry regions, in keeping with the definition of the 3.5-box climate model of LCH. The mean CERES FOV Tb values at 10.8 μm from VIRS channel 4 are used to identify CERES FOV with tropical cloudy-moist regions (i.e., the combination of UTA and DCC) using the criteria in LCH of Tb $<$ 260 K. LCH assume that the Tropics are divided sharply into dry and moist regions, with nominally 50% area coverage by each. Because "dry" conditions will be typical of subsidence and low-level clouds or clear sky, we define the dry region as the portion of the tropical oceans that contains the 50% of largest CERES LW flux measurements. Because LW flux will increase as water vapor, cloud height, and cloud amount decrease, this definition should consistently pick out the driest regions of the Tropics. All CERES FOVs that are neither cloudy moist (Tb $<$ 260 K), nor dry regions are considered to be in the clear-moist region defined in LCH. A check by plotting CERES FOVs on tropical maps confirms the characteristics of the three categories. For example, during the 1998 El Niño event (January–March), the frequency of cloudy moist over the equatorial central Pacific reached as high as approximately 50%; in the higher latitudes (e.g., 15°N in the Pacific) UTA clouds were rare and dry conditions dominated. The clear-moist regions generally were collocated more closely with cloudy-moist areas than with dry regions because of the moisture supply from cloudy-moist areas.

In this manner, for each day we classify each of the CERES tropical FOVs into one of the three tropical regions used in the analysis of LCH. Statistics are kept on the CERES albedo, SW flux, and LW flux for each tropical region. The average albedo values are determined separately for each of 10 solar zenith angle bins, and then a daily mean albedo is determined by insolation weighting of the individual values, just as in determination of a daily average reflected flux. Because the TRMM satellite orbit precesses through the complete 24-h diurnal cycle every 48 days, TRMM samples the entire diurnal cycle roughly 5 times in the 8-month period used in this analysis. As a result, the average LW fluxes and albedos used here properly represent averages across the full diurnal cycle in the Tropics.

3. Comparison of iris and CERES radiative fluxes

The tropical radiative properties observed by CERES are summarized in Table 1. The small difference of net radiation between clear- and cloudy-moist regions in this study is consistent with the small net cloud radiative forcing observed in ERBE and CERES data over the tropical regions. To compare with LCH results, their values are also listed in the table. There are many relatively small differences, but there are three major differences:

1) The frequency of cloudy-moist regions (Tb $<$ 260 K) is 10% in the present analysis versus 22% used by LCH. This was discussed in the previous section.

TABLE 1. Radiative properties for tropical regions. Here clrm is clear moist, and cldm is cloudy moist.

	CERES			Lindzen et al.		
	dry	clrm	cldm	dry	clrm	cldm
Frequency	0.5	0.4	0.1	0.5	0.28	0.22
Albedo	0.154	0.258	0.510	0.211	0.211	0.349
SW	338.7	297.1	196.2	315.9	315.9	260.6
LW	287.7	253.9	154.8	303.1	263.1	137.7
Net radiation	51.0	43.2	41.4	12.8	52.8	122.9
Net vs dry net		−7.8	−9.6		40.0	110.1
cldm vs clrm			−1.8			70.1

2) The CERES observed albedo for cloudy-moist regions is 0.51 versus the LCH albedo of 0.349. This is a very large difference and indicates that optically thicker clouds dominate the tropical regions with Tb < 260 K. Because optically thick tropical clouds at 260-K emission could be at altitudes as low as 6.5 km, some noncirrus clouds are certainly included in the CERES albedo, and their area feedback is invoked in the iris hypothesis. A better way to evaluate this effect would be to combine CERES cloud retrievals or infrared sounder cloud heights matched to CERES TOA fluxes. This should be possible in the near future using the *Terra* CERES SSF data product expected to complete validation in January of 2002. Nevertheless, when this is done, the UTA:DCC area relationship will also require reexamination.
3) The CERES cloudy-moist LW flux is 155 W m^{-2}, significantly higher than the value (138 W m^{-2}) of LCH.

It is relatively simple to understand the impact of these radiative flux changes on the iris hypothesis. In the simplest form of the iris, an SST increase causes a decrease in the area of cloudy moist (Tb < 260 K) and a corresponding increase in the area of clear moist. The impact of the energetics of this trade can be seen in the net radiation of cloudy-moist versus the net radiation of clear-moist areas (last row in Table 1). The LCH results imply a net radiation difference of 70.1 W m^{-2}, with less cloudy-moist area suggesting more radiative cooling and, therefore, a strong negative feedback. CERES results imply a net radiation difference of −1.8 W m^{-2}, suggesting slightly less radiative cooling for less cloudy-moist area, that is, a weak positive feedback. The inconsistency of tropical cloud radiative properties between the LCH model and observations is also found by FBH. For tropical high clouds, the net radiative forcing FBH estimated is about −1 W m^{-2}, which is close to our result. The cloud radiative properties in Table 1 have also been examined for the tropical western Pacific in this study. The values are very similar, except the area of clouds with Tb < 260 K increases to about 13%, a value close to what LCH found (cf. Fig. 5a of LCH).

Could the differences in our results and LCH be explained by thin cirrus at the edge of thicker anvil clouds being eliminated as SST increases? CERES observations found that for the threshold Tb < 260 K, the net radiation of the cloudy-moist regions is not sensitive to SST. With SST collected in every 1-K interval and its averaged values varying from 300 to 302 K where the majority (∼60%) of the clouds appear, the net radiation of the clouds changes from 40.2 to 43.4 W m^{-2} as compared with the mean value 41.4 W m^{-2} (cf. Table 1). Furthermore, when all high clouds, including the thin cirrus not detected by the threshold, are considered, the net radiative forcing (−1 W m^{-2}) estimated by FBH is close to our observation, as mentioned before. Thus, we conclude that changes in the net radiation of the cloudy-moist region with SST are not dominated by thin cirrus and the threshold Tb < 260 K has small effects on the net radiation budget of high clouds.

Table 1 shows that two-thirds of the change in net radiation result from the much larger cloud albedo and one-third from the larger LW fluxes in the CERES observations. The much smaller albedo and lower LW flux of LCH as compared with CERES data for the cloudy-moist region exaggerate cooling effects of LW radiation and minimize warming effects of solar radiation as the UTA amount decreases. Using the Fu–Liou (1993) radiative transfer model for 15-km-altitude ice clouds, a consistency check suggests that the albedo is very sensitive to cloud optical depth and should be larger than 0.4 for the clouds with 138 W m^{-2} LW radiation used in LCH. Lower-altitude clouds would require even higher albedos. If a moderate optical depth of 16 were used, the albedo would quickly increase up to more than 0.6.

4. Cloud feedback calculations

The cloud feedback simulations are based on the 3.5-box greenhouse model according to LCH but using the CERES observed values as inputs. The greenhouse model is essentially a radiative energy balance model, which assumes that the temperature gradients between surface and emission level within each box do not change with small climate perturbations and the surface temperatures of the Tropics and extratropics are 10 K above and below, respectively, the global mean surface temperature (currently 288 K). The major inputs for the model are CERES observations of the relative area, mean albedo, and equivalent emission temperature es-

TABLE 2. Parameters for 3.5-box greenhouse model. Here, clr is clear, cld is cloudy, m is moist, d is dry, t is tropical, et is extratropical, e is emission, and s is surface.

Symbol	Description	CERES	Lindzen et al.
A_{cldm}	Relative area of tropical cloudy-moist region	0.05	0.11
A_{clrm}	Relative area of tropical clear-moist region	0.2	0.14
r_{cldm}	Albedo of tropical cloudy-moist region	0.510	0.349
r_{clrm}	Albedo of tropical clear-moist region	0.258	0.211
tr_{cm}	Albedo of tropical moist region	0.308	0.272
tr_d	Albedo of tropical dry region	0.154	0.211
tr_t	Albedo of the Tropics	0.231	0.242
tr_{et}	Albedo of extratropics	0.417	0.402
T_{ecldm}	Emission temperature from A_{cldm} region	$T_{st} - 69.4$	$T_{st} - 76$
T_{eclrm}	Emission temperature from A_{clrm} region	$T_{st} - 39.3$	$T_{st} - 37$
T_{ed}	Emission temperature from tropical dry region	$T_{st} - 31.1$	$T_{st} - 27.6$
T_{eet}	Emission temperature from extratropics	$T_{set} - 31.0$	$T_{set} - 29.3$

timated from CERES LW flux for dry, clear-moist, and cloudy-moist regions. Table 2 lists detailed parameters for the model along with LCH values. Where values are identical in the two studies, they are not listed in the table, and can be found in Table 1 of LCH.

A full description of the 3.5-box model can be found in LCH. The objective here is to use the values in Tables 1 and 2 to run the model and to interpret the results. We also verified that our implementation of the model in LCH reproduced their results.

Figures 1a and 1b give the results of the simple climate model and are comparable to Fig. 10 of LCH. The results for changes in global average surface temperature as a function of change in the fraction of tropical cloudy moist (Tb < 260 K) are given in Fig. 1a, and the results for change in global average albedo are in Fig. 1b. The figures contain both the results of LCH (dashed lines) and the current study (solid lines) to facilitate direct comparison. The parameter γ is defined in LCH and is a sensitivity parameter that varies the relationship between tropical moist (the combination of clear moist and cloudy moist) and cloudy-moist regions. For $\gamma = 1$, the tropical moist area increases at the same rate as the increase in tropical cloudy-moist area. For $\gamma = 0$, the tropical moist area is fixed at 50% of the Tropics and is independent of the cloudy-moist area. The same values of γ used in LCH are used here.

The results in Figs. 1a,b follow directly from the discussion in the previous section. The net radiative effect of the cloudy-moist regions is switched in sign and is much lower in magnitude than those assumed in LCH. As a result, for a given change in tropical cloudy-moist area, the strong negative feedback in surface temperature in the LCH iris analysis becomes a weak positive feedback in our analysis (Fig. 1a). No cloud feedback would be a horizontal line (i.e., no effect on surface temperature) as the cloudy-moist area is changed. Figure 1b demonstrates that the albedo effect of the cloudy-moist area (i.e., the total of UTA and DCC clouds) is much larger in the current results than in those of LCH. These results demonstrate that if there were an IR iris, the earth would also have an anti–IR iris or SW iris that would counterbalance and overpower the IR iris for the earth's radiation.

It should be emphasized that the net cloud radiative effect calculated from CERES data is ‘‘small’’ only related to that of LCH. Even this small net radiative effect is significant for climate. For example, with 0.03 de-

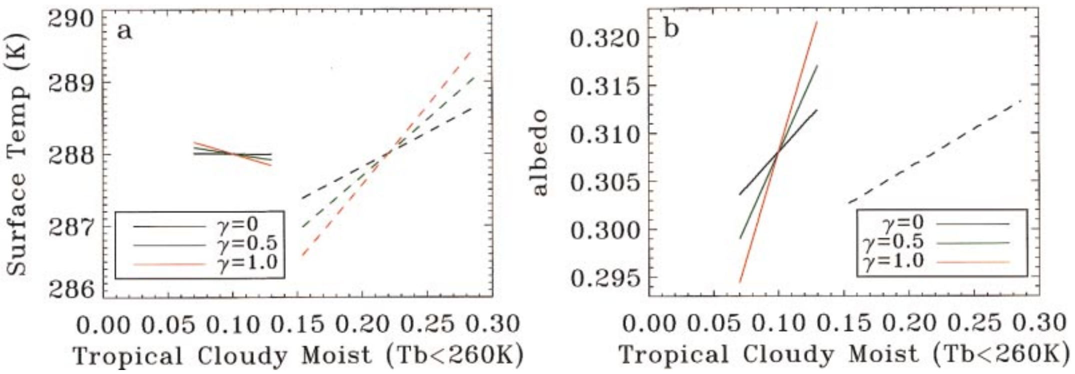

FIG. 1. Change in (a) global average surface temperature and (b) global albedo as the fractional amount of tropical cloudy-moist area (Tb < 260 K) is changed. Dashed curves are from Lindzen et al. (2001). Solid curves use TRMM CERES observed tropical fluxes as in Table 2. The strong negative cloud feedback in Lindzen et al. (2001) changes to weak positive feedback.

crease in the cloudy-moist area and the $\gamma = 0.5$ case, the radiative forcing is about 0.3 W m^{-2}, which is very close to that of tropospheric ozone (Albritton et al. 2001). Nevertheless, the effect is dramatically smaller than that in LCH and is of opposite sign. For $\gamma = 0$, 0.5, and 1 and 22% reduction of the cloudy-moist area, global mean surface temperature increases about 0.01, 0.06, and 0.12 K, respectively, using the CERES radiative fluxes in Table 2, as compared with -0.45, -0.75, and -1.1 K, respectively, of LCH.

5. Conclusions

The current study uses recent CERES TRMM satellite observations to test the iris hypothesis of Lindzen et al. (2001). We find that their study is too low in albedo by 0.161 and moderately low in the top-of-atmosphere longwave flux by 17 W m^{-2} for tropical cloudy-moist area (Tb $<$ 260 K). When combined, these two effects change the strong negative feedback in Lindzen et al. to a weaker positive feedback in this study. Thus, if there were an IR iris, the earth would also have an anti–IR iris or shortwave iris that would counterbalance the IR iris for the earth's radiation. Future studies should examine the use of infrared sounder cloud heights as opposed to a simple brightness temperature threshold to improve the analysis.

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