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Coincident occurrences of tropical individual cirrus clouds and deep convective systems derived from TRMM observations

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[1] Satellite measurements of cloud properties and atmospheric radiation were used to investigate the effect of spatial and temporal scales on the coincident occurrences of tropical individual cirrus clouds (ICCs) and deep convective systems (DCSs). There is little or even negative correlation between instantaneous occurrences of ICC and DCS in small areas. When spatial and temporal domains are increased, ICCs become more dependent on DCSs due to the origination of many ICCs from DCSs and moisture supply from the DCS in the upper troposphere for the ICCs to grow, resulting in significant positive correlation between the two types of clouds. The estimated radiative feedback due to the change in tropical high cloud area coverage with sea surface temperature appears small and about $-0.14\ \mathrm{Wm^{-2}K^{-1}}$, which would not cancel out the estimated anthropogenic forcing of doubled atmospheric CO_2. **Citation:** Lin, B., K.-M. Xu, P. Minnis, B. A. Wielicki, Y. Hu, L. Chambers, T.-F. Fan, and W. Sun (2007), Coincident occurrences of tropical individual cirrus clouds and deep convective systems derived from TRMM observations, *Geophys. Res. Lett.*, *34*, L14804, doi:10.1029/2007GL029768.

1. Introduction

[2] Tropical high clouds not only have strong influences on atmospheric radiation but also are one of driving factors for the variations of tropical precipitation and upper tropospheric humidity with sea surface temperature (SST), as demonstrated by recent satellite observations [*Luo and Rossow*, 2004; *Su et al.*, 2006; *Lin et al.*, 2006, and references therein]. There is some evidence suggesting that tropical high clouds may enhance the greenhouse effect through a positive water vapor feedback in warm climates [*Su et al.*, 2006]. Although much effort has been made to evaluate climate feedbacks of the high clouds from observations [e.g., *Ramanathan and Collins*, 1991; *Wallace*, 1992; *Fu et al.*, 1992; *Hartmann and Michelsen*, 1993, 2002; *Lindzen et al.*, 2001; *Del Genio and Kovari*, 2002; *Lin et al.*, 2002; *Chambers et al.*, 2002], quantitative and accurate estimates of climate feedbacks of these tropical clouds are still limited. Understanding the variations of these high clouds with SST is a critical first step to accurately estimate their climate feedbacks.

[3] There are generally two types of tropical high clouds: deep convective systems and individual cirrus clouds. A deep convective system (DCS) is a contiguous high cloud sheet with embedded active deep convective cores. The cores produce heavy precipitation and transport moisture to upper troposphere maintaining DCS stratiform precipitation and the main body of DCS high cloud sheet: cirrostratus/cirrus clouds. These cirrostratus/cirrus cloud sheets dominate DCS radiative effects. An individual cirrus cloud (ICC) is a tropical high cloud patch without any deep convective cores or simply any high clouds not belonging to a DCS. Because tropical convection is strongly organized, most tropical high clouds are DCSs [*Lin et al.*, 2006]. ICCs can be composed of dissipated DCSs, newly developing convective systems without surface precipitation, or locally developed in-situ cirrus clouds [*Luo and Rossow*, 2004]. These individual cirrus clouds are generally much thinner than DCSs and have significant influences on atmospheric longwave radiation. Both DCS and ICC are important contributors to climate sensitivity due to their influences on upper tropospheric humidity and the radiation balance. There are, however, considerably different interpretations of their roles in climate feedbacks. For example, *Lindzen et al.* [2001] suggested that the areal coverage of these tropical high clouds decreases with increasing temperature due to the effective removal of the moisture to be transported to the upper troposphere by increased precipitation and precipitation efficiency. Here, the areal coverage of a cloud in a region is defined as the ratio (in percent) of the area covered by the cloud to the total area of the region. *Ramanathan and Collins* [1991] and *Del Genio and Kovari* [2002] indicated that more tropical high clouds form in warmer climates due to enhanced convection. Results from cloud resolving model simulations with limited domain sizes and time periods showed that the column cloud fractions are slightly reduced as SST increases [*Tompkins and Craig*, 1999; *Wu and Moncrieff*, 1999; Z. A. Eitzen and K.-M. Xu, Sensitivity of a large ensemble of tropical convective systems to changes in the thermodynamic and dynamic forcings, submitted to *Journal of Atmospheric Science*, 2007, hereinafter referred to as Eitzen and Xu, submitted manuscript, 2007], but the upper-tropospheric cloud fractions could increase as SST rises in some models [*Tompkins and Craig*, 1999; Eitzen and Xu, submitted manuscript, 2007].

[4] Recently, *Lin et al.* [2006] investigated the DCS type of tropical high clouds using measurements from the Tropical Rainfall Measuring Mission (*TRMM*) satellite data during Clouds and the Earth's Radiant Energy System (CERES) *TRMM* period (January — August 1998) and found that the DCS areal coverage increases with SST despite the increases in both DCS precipitation and rainfall

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efficiency with SST. Higher sea surface temperature results in enhanced boundary layer moisture and the moisture transported into the upper troposphere. The increased transports of moisture available for cloud formation, along with changes in the cloud formation efficiency, likely contribute to the significant increase of DCS area coverage with SST.

[5] This study focuses on observations of the ICC type of tropical high clouds, especially the coincident occurrences of ICC and DCS using *TRMM* satellite measurements. The effects of temporal and spatial scales on the coincident occurrences of ICC and DCS are discussed. Section 2 introduces the data sets and analysis methods used in this study. Section 3 shows the results. Radiative feedbacks of these observed clouds on climate and summary are given in section 4.

2. Data Analysis

[6] Similar to our previous study [*Lin et al.*, 2006], this investigation analyzes *TRMM* data taken over oceans between 30°N and 30°S during January through August 1998. The time period is determined by CERES data availability. The CERES *TRMM* observations captured a transition from a strong El Niño during early 1998 to normal or weak La Niña tropical climate conditions, which includes large dynamic and thermodynamic changes needed to examine the radiation variations of tropical high clouds. The profound variations in the large-scale circulations and small-scale convective activities during this period also provide us a good chance to evaluate interrelationships of tropical high clouds at different scales. This paper focuses on the coincident occurrences of ICC and DCS. Measurements from three instruments on board the *TRMM* satellite: the CERES cross-track scanner, the Visible and Infrared Scanner (VIRS), and the *TRMM* Microwave Imager (TMI), are used in this study. The CERES scanner measures broadband shortwave (SW) and longwave (LW) radiation at a spatial resolution of about 10 km, while the VIRS monitors narrowband spectral visible, near-infrared, and infrared (IR) radiances at a nominal 2-km resolution over a 720-km swath. The TMI is used to detect precipitation and estimate precipitation intensity. TMI pixel sizes vary with frequency, from about 4.6 km × 7.2 km to 9.1 km × 63.2 km over a total swath width of 780 km.

[7] The basic data set is the CERES single scanner footprint (SSF) product (E. B. Geier et al., Clouds and the Earth's radiant energy system data management system single satellite footprint TOA/surface fluxes and clouds (SSF) collection document, release 2, version 1, 2003, 243 pp., available at http://asd-www.larc.nasa.gov/ceres/collect_guide/SSF_CG.pdf). The SST data used in this analysis, from the Reynolds SST analysis [*Reynolds and Smith*, 1994], are included in the SSF product. The CERES project processes VIRS measurements to detect cloudy and clear skies, and to estimate effective cloud top temperature and height, cloud fraction, and cloud thermodynamic phase [*Minnis et al.*, 2002]. The CERES cloud properties derived from 2-km resolution VIRS pixels are convolved into TMI 37-GHz field-of-views (FOVs) as in the work by *Ho et al.* [2003] to minimize spatial and temporal collocation errors. Rainfall rate data from the Goddard level-2 standard TMI products [*Kummerow et al.*, 2001] are registered to the collocated data.

[8] After collocating the CERES cloud products from VIRS with the TMI passive microwave measurements, we further match the data with the CERES SW and LW flux data. All CERES measurements within a 15-km radius of the center of each TMI tropical high cloud FOV are considered as matched CERES footprints. The average SW and LW fluxes for the matched CERES footprints, weighted by their proximity to the TMI FOVs, are calculated to represent the radiative properties of the high clouds that are covered by the TMI FOV.

[9] To use *TRMM* data in detecting and analyzing tropical high clouds, we first identify all tropical high clouds using thermodynamic phase (ice) and cloud top height (higher than 5 km) or 11-μm IR brightness temperature (less than 270 K) information of the collocated data. After this detection of high clouds, we search for DCSs. Each DCS includes at least one cold precipitating cell as a deep convective core and contiguous neighboring high clouds around the core as the main body of the DCS, as discussed by *Lin et al.* [2006]. All other tropical high clouds are considered as ICCs.

3. Results

[10] The interactions among tropical high clouds, moisture fields and radiation are very complicated processes. The frequency and areal coverage of high clouds, hereafter cloud areal coverage or simply cloud cover (in percent), are related to many environmental parameters, as shown by *Luo and Rossow* [2004] and *Lin et al.* [2006]. The present study mainly focuses on the effects of temporal and spatial scales on the coincident occurrences of two different types of the tropical high clouds, namely ICC and DCS. We will first show the analysis of their areal coverage at instantaneous and small spatial (1° × 1°) scales and then gradually extend the analysis to longer (inter-seasonal) temporal and larger (30° × 30°) spatial scales. The tropical high cloud radiative feedbacks are estimated based on the observed variability of the high clouds, which will be discussed in section 4.

[11] Figure 1 shows density plots of 36-hour composite cloud covers of ICCs and DCSs in spatial domains from 1° × 1° (upper left), 2.5° × 2.5° (upper right), 5° × 5° (lower left) to 10° × 10° (lower right) for the entire tropics (± 30° latitudes) during January 1998. The color codes changing from blue to red represent increasing co-occurrences of the two cloud types, as shown in the color bar. The 36-hour composites are used because at this temporal resolution, *TRMM* measurements almost cover the entire tropics and generally have no multiple observations at a single location, while at smaller time intervals, such as 24 hours, significant parts of the tropics are not scanned by the *TRMM* satellite. Thus, the observations at this time scale can be considered as instantaneous measurements. It can be seen from Figure 1 that at the smallest spatial scale (1° × 1°), statistically, the coverages by ICCs and DCSs are significantly negatively correlated. In a small area, more deep convection would generate more organized high clouds and suppress individual cirrus to develop simultaneously in the same area. This negative correlation is thus expected since the sum of the ICC and DCS covers cannot exceed 100%. When the spatial

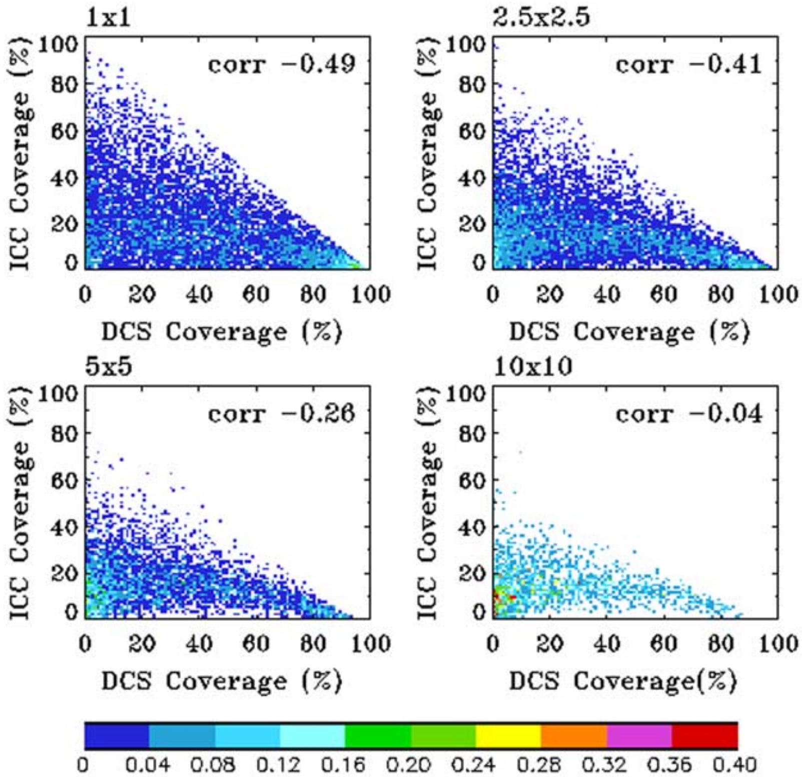

Figure 1. Density plots of 36-hourly composite cloud covers of individual cirrus clouds versus deep convective systems (DCS) for January 1998. The color codes of the density are shown in the color bar (in unit of percent). Spatial domains for the analysis increase from (top left) 1° × 1°, (top right) 2.5° × 2.5°, (bottom left) 5° × 5° to (bottom right) 10° × 10°.

domain increases from 2.5° × 2.5° to 10° × 10°, the negative correlation between ICC and DCS remains for high DCS coverage, but a positive correlation begins developing for a range of small DCS amounts, resulting in an insignificant correlation for the full range of DCS and ICC areal coverage. At very large spatial scales (e.g., 30° × 30°), the ICC occurrences are mainly dependent on the large-scale dynamics and thermodynamics of the tropics, and moisture availability in the upper troposphere, which, as discussed by *Lin et al.* [2006], is part of the climate effects of DCS. Thus, the ICC covers have a slightly positive correlation with their DCS counterparts (not shown), owing to the disappearance of the scatter in the high DCS areal coverage range. Note that similar results to those shown in Figure 1 are obtained for other months. The change from negative to positive correlation of ICC with DCS is around the spatial scale of 15° to 20° grid boxes. At this or larger scales, not only organized deep convective clouds, occupying generally a small part of the area, can supply moisture to upper troposphere enhancing cirrus development, but also some cirrus clouds at a distance from convection circulations can grow individually without direct influence from the DCS.

[12] The transition behavior for the relationships of ICC and DCS from small to large spatial scales in the instantaneous data can also be found in long temporal (8-month) composites of the satellite measurements. But from the temporal perspective, only positive relationships between ICC and DCS are observed (Figure 2), due to the elimination of weather noise from the temporal variations of the dynamics. The strong coincident occurrence of ICC and DCS at the longer time scales, especially when the spatial domain is very large (e.g. 30° × 30° grid boxes), reflects the climatological dependence of cirrus clouds on convection for their origination and moisture supply in the upper troposphere. Note that the upper left panel of Figure 2 covers spatial scales roughly only one thousandth those of the lower right panel. Basically, no large-scale scenes over long-time periods contain only deep convection or cirrus. The observed cloud covers of DCS and ICC are climatological accumulations of both types of clouds. Smaller scenes and shorter periods may sample arbitrary amounts of the two types of clouds produced by local instantaneous weather conditions and make the two types of clouds less correlated. The main reason for the different results from those shown in Figure 1 is that climatic signals are the main contributor to the results shown in Figure 2 while the variations caused by weather systems dominate the results shown in Figure 1. These climatic signals modulate the occurrences of both types of tropical clouds, which also explain the higher positive correlations for the larger spatial regions shown in Figure 2.

[13] Further evidence of coincident occurrences of ICC and DCS can be seen from binned data. Figure 3 shows the means of ICC (+), DCS (*) and total high cloud (Δ) areal coverage for each 1 K-SST interval using the 8-month dataset for the entire tropics. The variation of ICC directly follows that of DCS. As discussed by *Lin et al.* [2006], the total tropical high cloud cover is dominated by DCS. Although ICC (with areal coverage about 5 ∼ 10%) only

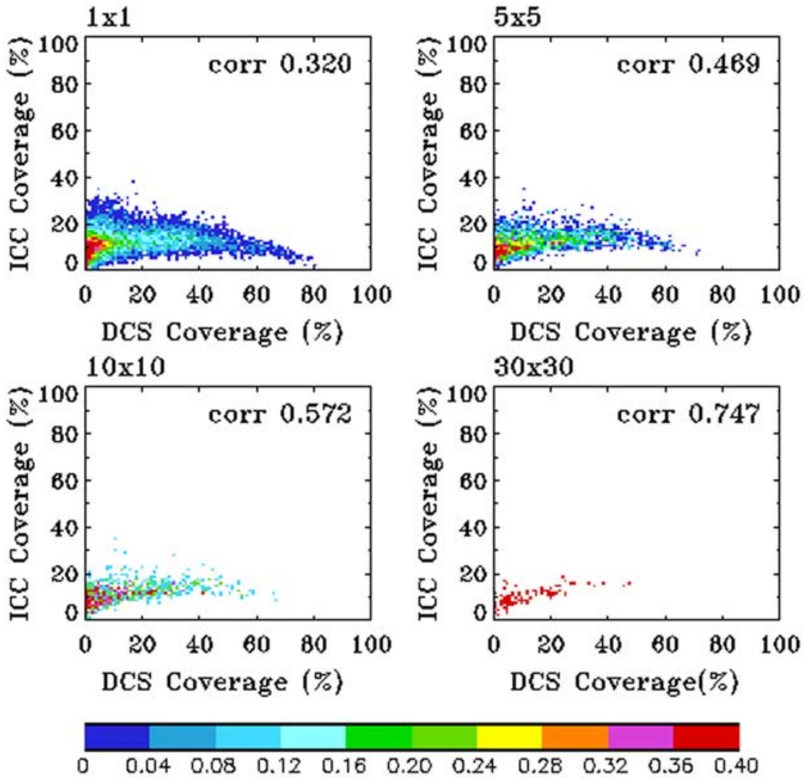

Figure 2. Same as Figure 1, except for data from 8 months of CERES TRMM measurements.

contributes a small fraction of the high clouds, their influence on climate, especially on the radiation balance, cannot be neglected. In most SST dynamic ranges (SST < 304 K), high (ICC and DCS) cloud cover in the tropics increases with temperature. A small decrease of the clouds in the warmest region (SST > ~304 K) is due to the weaker convergence occurring in those areas compared to that for their counterparts in slightly cooler (SST ~ 302 K) regions [*Lin et al.*, 2006]. The averaged increase rate of the high clouds with SST is about 2.8% per degree Kelvin, slightly higher than that for DCS alone obtained by *Lin et al.* [2006].

4. Discussion and Summary

[14] This study uses the measurements taken during January through August 1998 from multiple *TRMM* sensors, namely CERES, TMI and VIRS, to evaluate the relationship between ICCs and DCSs and the radiative effects of tropical high clouds. The measurements from *TRMM* satellite show that relating occurrences (or areal coverage) of ICCs to those of DCSs in small domains is limited because large extended instantaneous DCSs tend to fill most of the domain and to suppress ICCs precluding a reliable assessment of the ICCs. When the spatial or temporal domains are increased, it becomes clear that the ICCs depend on DCS coverage due to the origination of the ICC from the DCS and its accompanying moisture supply in the upper troposphere that maintains and grows the ICC. This results in significant positive correlations between the two types of tropical high clouds in large spatial and long temporal scales. This result suggests that the decrease of tropical high clouds with SST from model simulations [*Tompkins and Craig*, 1999; *Wu and Moncrieff*, 1999; Eitzen and Xu, submitted manuscript, 2007] is likely caused by the restricted spatial domains and perhaps limited simulation time periods used in these studies. However, the dynamic states were fixed in these SST sensitivity simulations, while the dynamic states in the observations might be slightly different for different SSTs.

[15] Based on our satellite observations tropical high clouds including both deep convection systems and individual cirrus clouds would increase when the tropics get warmer, which contradicts some suggestions of dehydration processes [*Lindzen et al.*, 2001]. The increase of high clouds with SST would produce certain climate radiative effects (i.e., feedbacks). Because high clouds may not be developed from a clear sky background, the commonly defined cloud

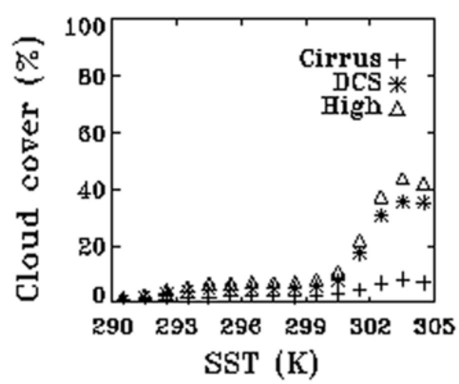

Figure 3. Mean ICC (+), DCS (*) and total high cloud (Δ) areal coverage as a function of SST for the entire tropics, January–August 1998.

radiative forcing, which is the radiative difference between cloudy and clear skies, cannot represent actual radiation changes well. Besides deep convective systems and individual cirrus clouds, fair weather low-level cumulus and stratocumulus clouds cover a significant part (~23%) of the tropics. Also, there are non-negligible amounts of middle-level clouds originally from shallow convection or cumulus congestus. To estimate high cloud radiative feedback, this study follows the idea of generalized radiative forcing of tropical high clouds [*Lin et al.*, 2006], which defines radiative forcing as the difference between high clouds and existing environmental conditions. These existing environmental conditions could include low and middle clouds, moist, or partially cloudy conditions, but not the skies with high clouds.

[16] The procedures for calculating the radiative effects from CERES measurements for tropical high clouds including both DCSs and ICCs are the same as those for DCS alone and can be found in the work by *Lin et al.* [2006]. The average net high cloud radiative forcing from environmental conditions after weighting by the distribution of high clouds on SST is relatively weak (-4.95 W/m^2) only slightly more than 1/3 of the radiative forcing computed relative to clear conditions. Since the average increase of tropical high cloud areal coverage with SST is about 2.8% per Kelvin, the radiative feedback due to a change in high cloud areal coverage is about $2.8\%/\mathrm{K} \times (-4.95\ \mathrm{W/m^2}) = -0.14\ \mathrm{W/m^2/K}$, which may be small compared to the estimated anthropogenic forcing of doubled atmospheric CO_2. This result suggests that the negative feedbacks of tropical high clouds are not likely to cancel the influence of increased atmospheric greenhouse gases on the climate. In addition to tropical high clouds, investigations of other types of clouds such as subtropical boundary-layer clouds are critical for overall understanding of cloud climate feedbacks and for improving predictions of future climate.

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References

Chambers, L., B. Lin, and D. Young (2002), New CERES data examined for evidence of tropical iris feedback, *J. Clim.*, *15*, 3719–3726.

Del Genio, A. D., and W. Kovari (2002), Climatic properties of tropical precipitating convection under varying environmental conditions, *J. Clim.*, *15*, 2597–2615.

Fu, R., A. Del Genio, B. Rossow, and W. T. Liu (1992), Are cirrus clouds a "thermostat" for tropical sea surface temperature?, *Nature*, *358*, 394.

Hartmann, D. L., and M. L. Michelsen (1993), Large-scale effects on the regulation of tropical sea surface temperature, *J. Clim.*, *6*, 2049–2062.

Hartmann, D. L., and M. L. Michelsen (2002), No evidence for iris, *Bull. Am. Meteorol. Soc.*, *83*, 249–254.

Ho, S., B. Lin, P. Minnis, and T. Fan (2003), Estimates of cloud vertical structure and water amount over tropical oceans using VIRS and TMI data, *J. Geophys. Res.*, *108*(D14), 4419, doi:10.1029/2002JD003298.

Kummerow, C., Y. Hong, W. S. Olson, S. Yang, R. F. Adler, J. McCollum, R. Ferraro, G. Petty, D.-B. Shin, and T. T. Wilheit (2001), The evolution of the Goddard profiling algorithm (GPROF) for rainfall estimation from passive microwave sensors, *J. Appl. Meteorol.*, *40*, 1801–1820.

Lin, B., B. Wielicki, L. Chambers, Y. Hu, and K.-M. Xu (2002), The Iris hypothesis: A negative or positive cloud feedback?, *J. Clim.*, *15*, 3–7.

Lin, B., B. Wielicki, P. Minnis, L. Chambers, K.-M. Xu, Y. Hu, and A. Fan (2006), The effect of environmental conditions on tropical deep convective systems observed from the TRMM satellite, *J. Clim.*, *19*, 5745–5761.

Lindzen, R. S., M.-D. Chou, and A. Hou (2001), Does the Earth have an adaptive infrared iris?, *Bull. Am. Meteorol. Soc.*, *82*, 417–432.

Luo, Z., and W. Rossow (2004), Characterizing tropical cirrus life cycle, evolution, and interaction with upper-tropospheric water vapor using Lagrangian trajectory analysis of satellite observations, *J. Clim.*, *17*, 4541–4563.

Minnis, P., et al. (2002), A global cloud database from VIRS and MODIS for CERES, paper presented at 3rd International Asia-Pacific Environmental Remote Sensing Symposium 2002: Remote Sensing of the Atmosphere, Ocean, Environment, and Space, Int. Soc for Opt. Eng., Hangzhou, China, 23–27 Oct. (Available at http://www-pm.larc.nasa.gov/ceres/pub/conference/Minnis.SPIE.02.pdf.)

Ramanathan, V., and W. Collins (1991), Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Nino, *Nature*, *351*, 27–32.

Reynolds, R. W., and T. M. Smith (1994), Improved global sea surface temperature analysis, *J. Clim.*, *7*, 929–948.

Su, H., W. G. Read, J. H. Jiang, J. W. Waters, D. L. Wu, and E. J. Fetzer (2006), Enhanced positive water vapor feedback associated with tropical deep convection: New evidence from Aura MLS, *Geophys. Res. Lett.*, *33*, L05709, doi:10.1029/2005GL025505.

Tompkins, A. M., and G. C. Craig (1999), Sensitivity of tropical convection to sea surface temperature in the absence of large-scale flow, *J. Clim.*, *12*, 462–476.

Wallace, J. (1992), Effect of deep convection on the regulation of tropical sea surface temperature, *Nature*, *357*, 230–231.

Wu, X., and M. W. Moncrieff (1999), Effects of sea surface temperature and large-scale dynamics on the thermodynamic equilibrium state and convection over the tropical western Pacific, *J. Geophys. Res.*, *104*, 6093–6100.

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