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Cloud structure anomalies over the tropical Pacific during the 1997/98 El Niño

Robert D. Cess and Minghua Zhang
Marine Sciences Research Center, State University of New York, Stony Brook, NY 11794-5000

Pi-Huan Wang
Science and Technology Corporation, Hampton, VA 23666-1340

Bruce A. Wielicki
NASA Langley Research Center, Hampton, VA 23681-2199

Abstract. Satellite measurements of both cloud vertical structure and cloud-radiative forcing have been used to show that during the strong 1997/98 El Niño there was a substantial change in cloud vertical structure over the tropical Pacific Ocean. Relative to normal years, cloud altitudes were lower in the western portion of the Pacific and higher in the eastern portion. The reason for these redistributions was a collapse of the Walker circulation and enhanced large-scale upward motion over the eastern Pacific, both caused by the lack of a zonal sea surface temperature gradient during the El Niño. It is proposed that these cloud structure changes, which significantly impact satellite measurements of the tropical Pacific's radiation budget, would serve as one useful means of testing cloud-climate interactions in climate models.

Introduction

Cloud-climate interactions comprise one of the greatest uncertainties in attempting to model climate change using general circulation models (GCMs), and there is a need to devise ways of testing such interactions within models. If a GCM is to properly portray long-term climate change, it in turn must replicate cloud changes associated with events occurring on shorter time scales. A comparison of seasonal changes of cloud radiative forcing, as produced by 18 GCMs, to satellite measurements showed substantial differences, and more importantly provided clues as to the deficiencies of some models [*Cess et al.*, 1997]. The present study suggests an additional test concerning changes in cloud vertical structure over the tropical Pacific Ocean during an episodic event, the strong 1997/98 El Niño.

Data

Data have been employed from the following sources:
1. The vertical distribution of clouds based on observations by the Stratospheric Aerosol and Gas Experiment (SAGE) II [*Wang et al.*, 1995].
2. Cloud-radiative forcing (CRF) as determined for a 5-yr period (1985-1989) by the Earth Radiation Budget Experiment (ERBE) and for the first 4 months of 1998 by the Clouds and the Earth's Radiant Energy System (CERES) instrument on the Tropical Rainfall Measuring Mission (TRMM) Satellite. These data sets are described by *Cess et al.* [2001], who also provide a discussion of the consistency and accuracy of the ERBE and CERES data.
3. Zonal winds from the National Environmental Prediction Center/National Center for Atmospheric Research (NCEP/NCAR) reanalysis [*Kistler et al.*, 2001].

Analysis

The SAGE II instrument detects clouds by using the Sun-occultation technique, and thus it provides reliable information of the vertical distribution of cloud frequencies (1 km vertical resolution). Vertical profiles of cumulative cloud frequency are shown in Fig. 1 for the western (5°S-10°N, 100°E-170°E) and eastern (7.5°S-7.5°N, 200°E-280°E) regions of the tropical Pacific, domains that were chosen to produce statistically meaningful sampling. The cumulative cloud frequency is the frequency of clouds found by SAGE II above a given altitude. These data comprise 5-month means (DJFMA) with Dec. referring to the prior year, and these 5 months represent the strongest period of the 1997/98 El Niño. Clearly, relative to other years, during 1998 there is a vertical redistribution towards lower clouds in the west and higher clouds in the east. The 1987 DJFMA means are similar to the 1985-1991 means for the western region (Fig. 1A) and depart only slightly for the eastern region (Fig. 1B), even though 1987 was a modest El Niño year, emphasizing that 1998 is unusual, even for El Niño periods.

The ERBE/CERES CRF data, analyzed as in (3), are consistent with these west/east cloud vertical redistributions, as well as again emphasizing that 1998 was an unusual El Niño period relative to 1987. The ERBE/CERES top-of-the-atmosphere (TOA) measurements of reflected shortwave (SW) and emitted longwave (LW) provide the SW and LW components of CRF [*Ramanathan et al.*, 1989], for which

$$\text{SW CRF} = R_C - R$$

where R denotes the TOA all-sky reflected SW and R_C that for clear skies, while

$$\text{LW CRF} = F_C - F$$

where F and F_C, respectively, denote the all-sky and clear-sky TOA emitted LW. Typically SW CRF is negative (cooling)

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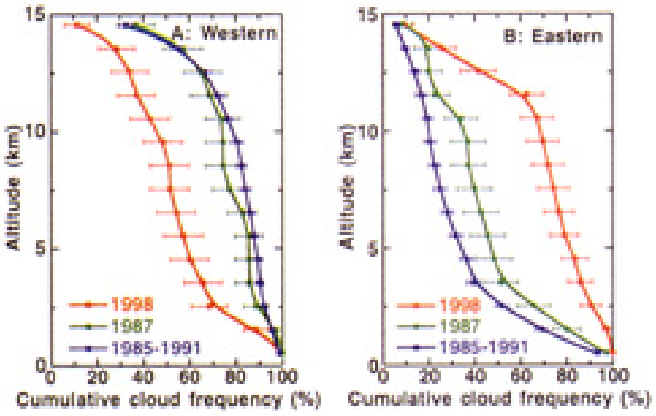

Figure 1. (A) Vertical profiles of the SAGE II cumulative cloud frequency over the western region of the tropical Pacific Ocean (5^{o}S-10^{o}N, 100^{o}E-170^{o}E). These comprise 5-month means (DJFMA), with Dec. referring to the prior year. The horizontal bars represent 1 standard deviation. (B) The same as (A) but for the eastern region (7.5^{o}S-7.5^{o}N, 200^{o}E-280^{o}E). Comparison of the 1987 El Niño (green) and the 1998 El Niño (red) shows the dramatic cloud height response in the 1998 El Niño event for both regions of the Pacific. Median cloud heights in 1998 change by a factor of two.

and LW CRF positive (warming). The Net CRF is simply the sum of the components

$$\text{Net CRF} = \text{SW CRF} + \text{LW CRF}$$

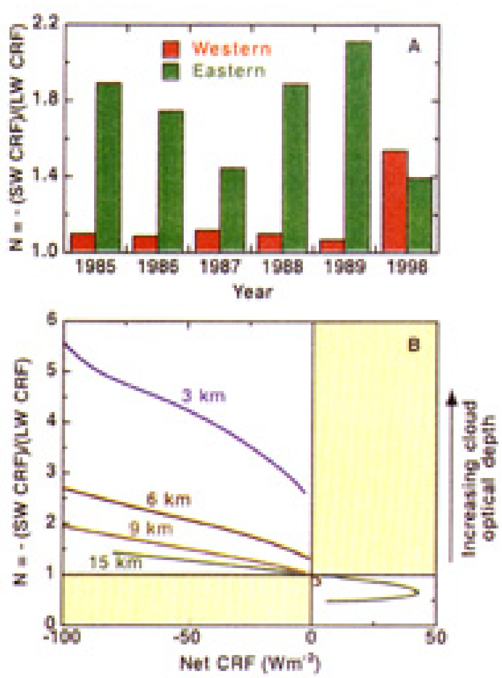

Figure. 2. (A) Four-month means (JFMA) of the ratio N = -(SW CRF)/(LW CRF) for each of the 6 ERBE/CERES years and for the western (5^{o}S-10^{o}N, 100^{o}E-170^{o}E) and eastern (7.5^{o}S-7.5^{o}N, 200^{o}E-280^{o}E) regions of the tropical Pacific Ocean. (B) Model calculations of N versus Net CRF for cloud-top altitudes of 15, 9, 6 and 3km. The shaded areas represent domains that are not physically possible (N denoting warming but Net CRF denoting cooling and vice versa).

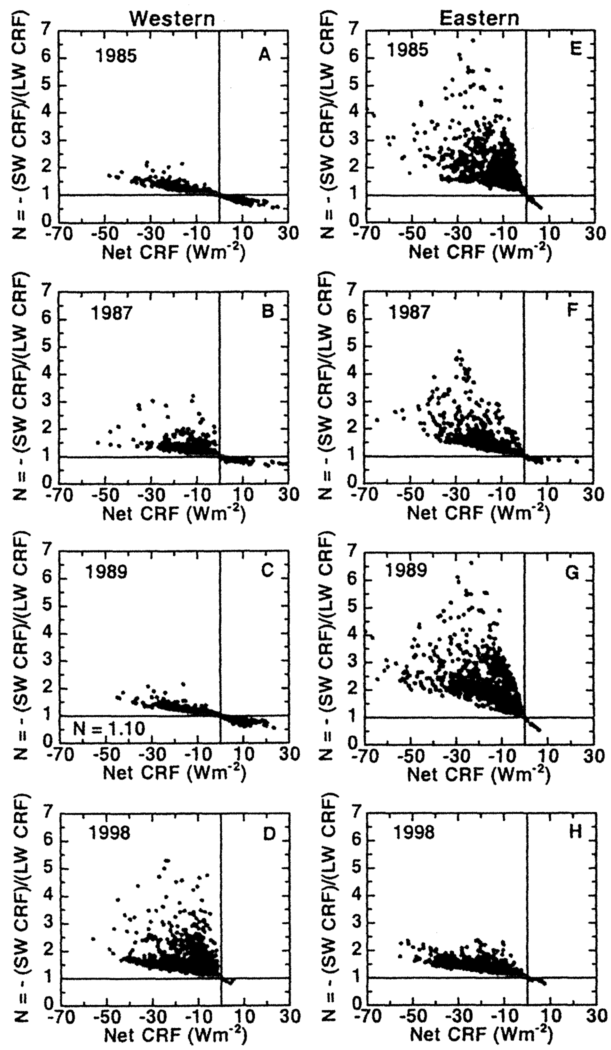

Figure 3. (A-D) Scatter plots of N versus Net CRF for the western region of the tropical pacific and for the designated years. (E-H) The same as (A-D) but for the eastern region.

so that cancellation between SW CRF cooling and LW CRF warming (Net CRF = 0) can be expressed by the ratio

$$N = -\,(\text{SW CRF})/(\text{LW CRF}) = 1$$

If N > 1, SW cooling dominates.

The ratio N has been evaluated by performing JFMA averages of the ERBE data for each of the 5 ERBE years (1985-1989) and of the CERES data for JFMA 1998, as shown in Fig. 2A. These are spatial averages over the same regions as for the SAGE II data. For the western region during 1985-1989, there is near compensation ($N \approx 1.1$) by the SW and LW components of CRF, but as in (3) SW cooling dominates in 1998. For the eastern region SW cooling dominates for all 6 years, but with considerable interannual variability; there is a reduction of N in 1987 (modest El Niño) and a further reduction in 1998 (strong El Niño) with N actually being less than for the western region.

To aid in the understanding of how N is influenced by cloud vertical structure, a radiative transfer model was used to produce the results shown in Fig. 2B, in which SW versus LW CRF compensation corresponds to the N = 1 and Net CRF = 0 intercept. As in *Cess et al* [2001], the radiation

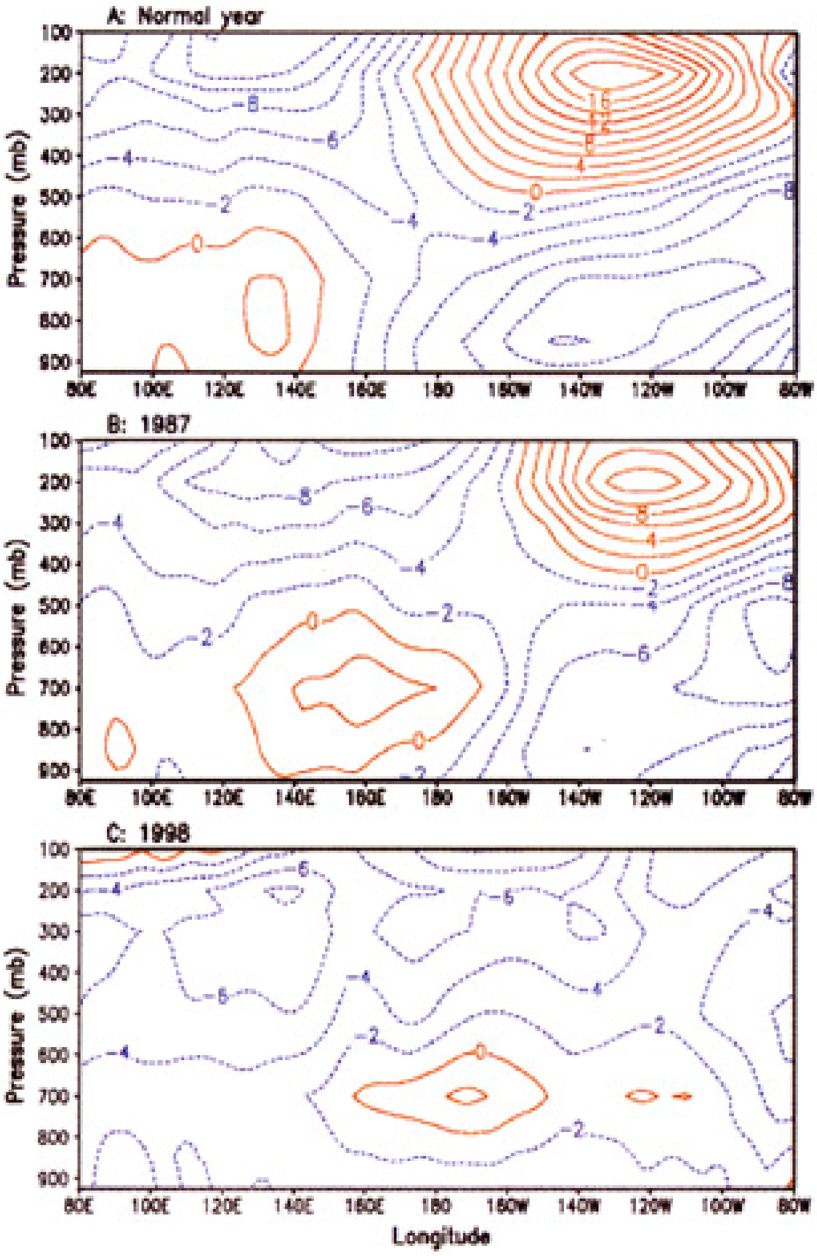

Figure 4. Pressure-longitude cross sections of zonal wind (ms^{-1}) averaged from $5^{O}S$ to $5^{O}N$ and for 4 months (JFMA). (A) Average of 1985, 1986 and 1989 (normal years). (B) 1987 (modest El Niño). (C) 1998 (strong El Niño).

model is from *Fu and Liou* [1993]. Inputs to the model include a surface albedo of 0.1 and a solar zenith angle of 60^{O}. The intent is to show a reasonable approximation of the results expected, rather than to exactly model any particular case. For the cloud-top altitude of 15 km, as cloud optical depth increases (progressing from bottom to top), both cloud emmisivity and albedo increase, but with the former dominating so that Net CRF increases (warming). This reverses when the albedo increases more rapidly than emissivity which asymptotes to unity, and ultimately Net CRF becomes negative (cooling). Because they are warmer, middle- and low-level clouds have smaller LW CRF, and hence larger N and smaller Net CRF, than high-level clouds. The model calculations are for a cloud fraction of unity, Since N is invariant to cloud fraction while Net CRF is not [*Cess et al.*, 2001; *Kiehl,* 1994], inclusion of cloud fraction would produce a horizontal progression of points with Net CRF going to zero as cloud fraction tends to zero. The 15-km cloud depicted in Fig. 2B can be thought of as representing thin cirrus (small optical depths) on the right to deep-convective clouds (optically thick) at the leftward termination of the curve.

Scatter plots of N versus Net CRF are given in Fig. 3 for both the western and eastern regions. Each point represents an ERBE/CERES monthly mean (for the first 4 months of each year) and $2.5^{O}\times2.5^{O}$ grid average, and 1985 and 1989 represent normal years. From the above discussion, the data for the western region represent areas dominated by high clouds spanning from thin cirrus on the right to deep-convective clouds on the left. The radiometric measurements cannot, however, preclude the existence of middle- and low-level clouds in conjunction with high-level clouds. A small population of middle-level clouds are impacting N (larger N) during the moderate 1987 El Niño, compared with a large population in the strong 1998 El Niño. Conversely, for the eastern region the two normal years are similar to the western region for 1998, while 1998 more closely resembles the two normal years for the western region. These normal year versus 1998 western/eastern reversals, as also demonstrated by the spatial averages of Fig. 2A, are consistent with the SAGE II western/eastern reversals of Fig. 1. Thus the two data sets are consistent in their portrayals of substantial cloud vertical redistributions in the tropical Pacific.

The reason for these vertical redistributions can be traced to substantial changes in the Walker circulation and the distribution of large-scale upward motion during 1998. Figure 4 shows height-longitude cross sections of zonal wind, averaged from $5^{O}S$ to $5^{O}N$ and for January through April, for a normal year (average of 1985, 1986 and 1989), 1987 and 1998. In a normal year, east of $140^{O}E$ there are well-defined easterlies in the lower troposphere and returning westeries in the upper troposphere, while to the west the circulation is reversed. The upward branch of the Walker circulation is centered between $140^{O}E$ and $160^{O}E$, which corresponds to strong convection that produces the high clouds in the western region (Figs. 3A and 3C). The downward branch of the Walker circulation is located to the east of $200^{O}E$, with subsidence air suppressing deep convection and producing shallow stratus and stratocumulus clouds (Figs. 3E and 3G). This Walker circulation is a direct response of the atmospheric circulation to the western warm pool and eastern cold tongue distributions of sea surface temperature (SST) for normal years.

In 1987 (modest El Niño) the magnitude of the easterlies and westerlies has decreased, and there is a shift of the upward branch of the Walker circulation to the east of the dateline. The Walker circulation has all but ceased in 1998 (strong El Niño), and the westerlies east of $180^{O}E$ in the upper troposphere have disappeared. This collapse of the Walker circulation is directly associated with the lack of a zonal SST gradient in 1998 as demonstrated in Fig. 7 of *Cess et al.* [2001]. The corresponding vertical velocity in the NCEP/NCAR reanalysis (not shown) demonstrates stronger upward motions to the east $180^{O}E$ than those to the west, thereby altering the vertical cloud structure in these two regions of the tropical Pacific (Figs. 3D and 3H). This enhanced upward motion is a reflection of the stronger Hadley circulation over the eastern Pacific. The NCEP/NCAR reanalysis shows a significant weakening of the Walker cell during the strong El Niño of 1983, but unlike 1998, the cell is still present.

Summary

The lack of a zonal SST gradient in the tropical Pacific Ocean during the 1997/98 El Niño caused a collapse of the Walker circulation and enhanced upward motion over the eastern Pacific, which resulted, on average, in lower clouds in the western portion of the Pacific and higher clouds in eastern portion. This by itself provides new information concerning cloud structure changes in the tropical Pacific associated with strong El Niño events. But of equal importance is that it provides a potentially important test of climate models. For simulations with an atmospheric GCM using prescribed SSTs, the lack of a zonal SST gradient in the Pacific during this El Niño is imposed upon the GCM as a boundary condition. Thus if a model contains realistic cloud parameterizations, it should replicate the substantial cloud redistributions that have been demonstrated with the satellite observations. We are, however, unaware of a model that does this.

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R. D. Cess and M. Zhang, Marine Sciences Research Center, State University of New York, Stony Brook, NY 11794-5000, (email: rcess or mzhang@notes.cc.sunysb.edu)

P. Wang, Science and Technology Corporation, Hampton, VA 23666-1340, (email: p.wang@larc.nasa.gov)

B. A. Wielick, NASA Langley Research Center, Hampton, VA 23681-2199, (email: b.a.wielicki@larc.nasa.gov)

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