Surface cloud forcing in the east Pacific stratus deck/cold tongue/ITCZ complex

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Abstract:

Data from the Eastern Pacific Investigation of Climate Studies (EPIC) mooring array are used to evaluate annual cycle of surface cloud forcing in the far eastern Pacific stratus cloud deck/cold tongue/Intertropical Convergence Zone (ITCZ) complex. Data include downwelling surface solar and longwave radiation from ten EPIC-enhanced Tropical Atmosphere and Ocean (TAO) moorings from 8°S, 95°W to 12°N, 95°W, and the Woods Hole IMET mooring in the stratus cloud deck region at 20°S, 85°W. Surface cloud forcing is defined as the observed downwelling radiation at the surface minus the clear-sky value. Solar cloud forcing and longwave cloud forcing are anticorrelated at all latitudes from 12°N through 20°S: clouds tended to reduce the solar radiation and increase the longwave radiation at the surface. However, the relative amount of solar radiation reduction and longwave increase depends upon cloud type and varies with latitude. A statistical relationship between solar and longwave surface cloud forcing is developed for rainy and dry periods in six latitudinal regions: northeast tropical warm pool, ITCZ, frontal zone, cold tongue, southern, and stratus deck regions. The buoy cloud forcing observations and empirical relations are used as benchmarks to evaluate surface cloud forcing in the ISCCP FD dataset, NCEP2 reanalysis, and 40-year ECMWF Re-Analysis (ERA40). ISCCP compared well with the buoy measurements, although the ISCCP solar cloud forcing appears to be too weak (solar radiation too strong) by ~ $20Wm^{-2}$. Ad hoc corrections to the ISCCP field are discussed. ERA40 and NCEP2 solar cloud forcing showed large discrepancies with observations. In particular the NCEP2 cloud forcing at the equator was nearly identical to the ITCZ region, and thus had

significantly larger solar cloud forcing and smaller longwave cloud forcing than observed.

1. Introduction

Clouds have both a cooling and warming effect on the Earth’s surface. Because clouds reflect solar radiation back to space, shortwave (solar) cloud forcing acts as a cooling effect, a reduction in the solar radiation that warms the Earth’s surface. But clouds also have a warming effect through their emission of longwave infrared (terrestrial) radiation, thereby increasing downwelling longwave radiation at the Earth’s surface. The relative amount of surface warming and cooling by clouds (i.e., relative amount of longwave and shortwave surface cloud forcing) depends upon many factors including cloud base height, cloud thickness, background moisture, and aerosol distributions. It is thus not surprising that models have difficulties obtaining realistic radiative properties (Cess et al. 1989, 1990, 1996; etc.). Indeed, both the IPCC second and third assessment reports state that “the single largest uncertainty in determining the climate sensitivity to either natural or anthropogenic changes are clouds and their effects on radiation and their role in the hydrological cycle” (Kattenberg et al. 1996, p. 345; Moore 2001, p. 776). Both assessments call for comparisons of model simulations with observations.

In this analysis we use surface shortwave and longwave cloud forcing measurements from eleven moorings in the far-eastern tropical Pacific to provide benchmarks for satellite, numerical weather prediction models, and atmospheric climate models. The eastern tropical Pacific near the Pan-American landmass is characterized by a complicated meridional cloud structure, with a persistent stratus deck shading the cool southern hemisphere waters and deep convection in the intertropical convergence zone (ITCZ) over the warm surface waters north of the equator. Along the equator, upwelling causes a “cold tongue” of water to extend westward from the coast, with a sharp sea surface temperature (SST) front on its northern flank. Because the planetary boundary layer (PBL) tends to be capped by a strong temperature inversion over the cold tongue and to be destabilized over the warm water, the SST front tends to induce a front in the cloud structure (Hashizume et al. 2002; Chelton et al 2001; Xie et al. 1998; deSzoeke et al 2004).

The stratus deck/cold tongue/ITCZ complex has a strong seasonal cycle, as illustrated by figs. 1 and 2: When the trade winds weaken during January-March, the cold tongue recedes and a double ITCZ straddling the equator often forms (Lietzke et al 2001; Zhang 2001). These changes have substantial impacts on fractional cloud cover and type. The eastern tropical Pacific also experiences significant interannual variability, especially in association with El Niño –Southern Oscillation (ENSO). During El Niño warm events, deep convection can occur near the equator and the meridional asymmetry of the cloud structure is weakened (Wallace et al. 1998).

General circulation models (GCM), although steadily improving, are not able to reproduce much of this structure and variability (Mechoso et al. 1995, etc.). Common problems include a warm SST bias in the stratocumulus region, a cool SST bias in the equatorial cold tongue, and a persistent double ITCZ. Many of these unrealistic features can be attributed to poor cloud parameterizations, improper cloud formation, and incorrect cloud radiative properties (Philander et al. 1996). In a concerted effort to improve these GCMs, a 5-year experiment, the Eastern Pacific Investigation of Climate Studies (EPIC), was initiated in 1999. As part of enhanced monitoring for EPIC, eleven surface moorings in the far eastern tropical Pacific were equipped with a suite of instrumentation, including shortwave and longwave radiometers. Although some of the moorings suffered losses from fishing-related vandalism, up to 4 years of solar and longwave cloud forcing measurements were obtained.

In this paper we use data from the EPIC mooring array to analyze structure and variability of surface cloud forcing in the eastern tropical Pacific. Cloud forcing properties are analyzed in separate regions, and for precipitating and non-precipitating periods using Tropical Rainfall Measuring Mission (TRMM) satellite precipitation measurements. Using in situ buoy measurements, surface cloud forcing is estimated and their monthly averages are compared to model-based numerical weather prediction (NWP) and satellite products. In particular, we evaluate commonly used global cloud forcing products, namely fields from the European Center for Medium Range Weather Forecasting (ECMWF) Re-Analysis (ERA40), the NCEP2 Reanalysis, and the International Satellite Cloud Climatology Project (ISCCP). Although sources of errors are not diagnosed, deviations from observations presented here provide a measure of the products' ability to quantify the radiative effects of clouds.

2. Methodology and Data

Cloud forcing at the surface, $CFRx$, is defined here as the difference between the observed downwelling radiation Rx and the downwelling radiation at the surface expected under clearskies (skies with no clouds), Rx_0:

$$CFRx = Rx - Rx_0 \qquad (1)$$

where the subscript x refers to either the l longwave or s shortwave components. In this section, we describe data sources for surface solar and longwave cloud forcing evaluated from moored buoys, and cloud forcing fields from ERA40, NCEP2 reanalysis, and ISCCP, as well as the TRMM rainfall fields used to identify precipitating and non-precipitating periods.

a. EPIC Data

EPIC moorings used in this analysis include the enhanced Tropical Atmosphere and Ocean (TAO) moorings along 95°W (at 8°S, 5°S, 2°S, 0°, 2°N, 3.5°N, 5°N, 8°N, 10°N, 12°N) and the Woods Hole IMET mooring in the stratus deck region at 20°S, 85°W (Fig. 1). Both moorings have similar suites of surface instrumentation (McPhaden et al. 1998; Payne et al. 2002; Cronin et al. 2003; Weller et al. 2004), including solar and longwave radiation (the primary variables in this analysis), wind speed and direction, air temperature, relative humidity, barometric pressure, rain rate, and sea surface temperature.

Both TAO and IMET systems used Eppley Laboratories, Inc. Precision Spectral Pyranometers (PSP) to monitor downwelling shortwave radiation and the Precision Infrared Radiometers (PIR) to monitor downwelling longwave radiation. Although IMET and TAO systems each had slightly different mounting, electronic designs, and calibration procedures (Payne et al. 2002), both PIR systems computed downwelling longwave radiation from thermopile voltage, dome temperature, and casing temperature measurements (Fairall et al. 1998). TAO radiometers sampled at 1 Hz from which 2-minute averages were computed. IMET radiometers sampled at 5-second intervals from which 1-minute averages were computed. Both sets of PSP and PIR radiometers have root-mean-square errors less than approximately 10 Wm^{-2} based upon manufacture specification, analyses of pre- and post-calibrations, and ship-buoy and shore-based side-by-side comparisons (Payne et al. 2002). For the PIR, the largest sources of error were calibration drift and temperature gradients on the casing. For the PSP, the largest sources of error were calibration uncertainties and mean and time-varying tilts in the mast. Due to fishing-related vandalism, several 95°W TAO moorings were recovered with bent radiometer masts. Tilted masts can produce relatively large error in the daily averaged solar radiation magnitude on clear days when the angle is directed in the meridional plane (Katsaros and DeVault 1986; Medovaya et al. 2002). TAO buoys, however, are expected to vary in their orientation and thus monthly averaging will tend to reduce errors caused by a bent mast. Records with a sudden drop in magnitude that were recovered damaged or were not recovered are not included in the analysis.

Hourly averages of surface IMET data and daily averages of all TAO data were telemetered to shore in near real time via Service Argos. High resolution TAO data are available only after the mooring is recovered. Because the 95°W TAO moorings suffered substantial losses due to fishing-related vandalism, telemetered daily-averaged data are used when high-resolution data were not available. Use of daily-averaged data during these periods has minimal effect on the monthly-averaged cloud forcing estimates.

The 20°S, 85°W site has been occupied by a WHOI IMET mooring since October 2000. A research ship visits the site each year around October to recover and redeploy a fresh system and perform at-sea comparisons within 0.5 kilometers of the buoy. Solar radiometers were first deployed on the ten EPIC-enhanced TAO 95°W moorings in November 1999; longwave radiometers were deployed 6 months later in April 2000. Final recovery of the TAO EPIC enhancements was in November 2003, although because of data losses, the analysis here ends in August 2003. TAO moorings were visited by a NOAA ship (either *Ron Brown* or *Ka'imimoana*) at 6-month intervals to perform repairs and necessary recoveries and deployments. These cruises were also opportunities for boundary layer measurements, including atmospheric sounding profiles, which will be used in this analysis.

To estimate surface cloud forcing, the observed "full-sky" radiation is compared to the radiation that would have occurred in conditions of clear skies (1). Expected clear-sky solar and longwave radiation estimates require a model. Following Hare et al. (2004), we use the Iqbal (1988) solar radiation clear-sky model and the Hare et al. (2004) longwave clear-sky model with the buoy meteorological observations as input.

i. Clear-sky solar radiation

Clear-sky solar radiation at the top of the atmosphere can be determined based on solar constant (set as 1367 Wm^{-2} (Lean 1993)) and calculations of the zenith angle. Between the top of the atmosphere and the surface, clear-sky solar radiation is reduced by transmission properties of the atmosphere, which Iqbal (1988) parameterizes in terms of integrated water vapor, aerosol optical thickness within different wavelength bands, and the ozone-layer optical thickness. Since we have only surface values, we further parameterize the integrated water vapor (IV) in terms of the surface specific humidity measurements ($IV = b\, q_a$) where the seasonally and latitudinally varying scale value b is determined from ERA-40. Likewise, a biannually varying optical thickness is used based upon measurements from the NOAA ship (Hare et al. 2004). With shipboard observations from EPIC, Hare et al (2004) daily averaged solar flux has a root-mean-square scatter of $\pm 7\text{Wm}^{-2}$.

ii. Clear-sky longwave radiation

Clear-sky longwave (or infrared, IR) radiation depends upon moisture,

$$R_{ld\,0} = e_{e0} s T_a^4 - 3.5 \qquad (2)$$

where T_a is the air temperature in units Kelvin, σ is the Stefan-Boltz constant, and e_{e0} is the effective emissivity for clear skies, parameterized in terms of the surface specific humidity q_a, integrated water vapor *IV*, and latitude *y* according to Hare et al. 2004:

$$e_{e0} = A + B\sqrt{q_a} - 0.0188 + 0.0063 * IV$$

$$A = 0.50 + \frac{0.13}{60} abs(y) \quad ; \quad B = 0.091 - \frac{0.03}{60} abs(y)$$

The 3.5 Wm^{-2} bias removed from the clearsky computation in (1) accounts for the lower height of sensors on buoys relative to that on ships. As described in the previous subsection, integrated water vapor (IV) is estimated from specific humidity and a scale value from ERA-40. Based on comparisons with shipboard measurements, the model has a scatter of $\pm 6\ \text{Wm}^{-2}$ for daily averaged downward IR flux.

iii. implications for accuracy of buoy CF estimates

Hare et al. (2004) find that with these methods, the uncertainty of daily-averaged CF is about 7 Wm^{-2} for both IR and solar flux using the well-tended ship radiometers and clear-sky model parameters tuned to the data base. Using untended buoy radiometers with the modeled clear-sky radiation, CF uncertainties are expected to be 12-17 Wm^{-2} for solar cloud forcing and 11-15 Wm^{-2} for longwave cloud forcing.

b. ISCCP cloud forcing

International Satellite Cloud Climatology Project (ISCCP) downwelling surface shortwave and longwave cloud forcing monthly data (FD data set) were also evaluated (Zhang et al. 1995, Rossow and Schiffer, 1999). The fluxes are computed using an updated radiative transfer model from the Goddard Institute for Space Studies (GISS) GCM and a collection of physical cloud and surface properties based on ISCCP data, including daily atmospheric profiles of temperature and humidity (NOAA Television InfraRed Observation Satellites TIROS operational vertical sounder; daily ozone abundances (total ozone mapping spectrometer); and various climatologies. The parameters considered here include clear-sky, and full-sky shortwave and longwave radiative fluxes at the surface. ISCCP results are on a 3-hour and 280 km grid (equal-area map equivalent to 2.5° latitude-longitude at the equator), from which monthly averages are computed and downloaded. ISCCP data are available only through June 2001.

c. NCEP2 reanalysis cloud forcing

The NCEP/DOE AMIP-II Reanalysis (NCEP2) is a follow-on to the NCEP/NCAR reanalysis project (Kanamitsu et al. 2002). NCEP2 uses an updated forecast model, updated data assimilation system, improved diagnostic outputs, and fixes for the known processing problems of the NCEP/NCAR Reanalysis. NCEP2 monthly-averaged surface downwelling solar and longwave cloud forcing and clear-sky fields are on a ~1.9° grid and extend through August 2003.

d. Cloud forcing from 40-year ECMWF Re-Analysis (ERA40)

The 40-year ECMWF Re-Analysis (ERA40) is a follow-on to the ERA15 project (Simmons and Gibson 2000, Simmons 2001). ERA40 uses a finer resolution of the planetary boundary layer, an improved variational data assimilation system with a refined numerical model, and assimilates a wider range of satellite data. In particular, ERA40 includes reanalysis of scatterometer winds, special sensor microwave imager (SSMI) radiance, ozone products and high resolution infared spectrometer ozone-channel radiances. Monthly-averaged ERA40 fields are on a 2.5 degree grid and extend through July 2002.

e. TRMM Rainfall

Regions with precipitation have different cloud populations than those without, and hence would be expected to also have different cloud forcing. To discriminate between these two situations, we use monthly rain rates and their error estimates from the level 3 (3B-43) TRMM product. The 3B-43 algorithm uses TRMM and other sources, namely TRMM, geosynchronous IR, and rain gauges to produce the "best" precipitation estimate in the TRMM region. The monthly averaged rain rates and error estimates are on a 1 degree grid. In our analysis we identify significant rainfall as rain rates that are larger than the provided root-mean-square error estimate. Likewise, if the TRMM rain rate was less than the provided error estimate, then the month was deemed dry to within error estimate.

3. Results

a. Surface cloud forcing time series

Solar cloud forcing (Fig. 3) and longwave cloud forcing (Fig. 4) evaluated from the four sources (buoy, ISCCP, NCEP2, ERA40) show qualitatively similar features. As expected, deep convection associated with the ITCZ results in large solar cloud forcing (reduction in downwelling solar radiation) with a strong seasonal cycle. In particular, the shadowing effect of the deep convection has a seasonal migration similar to the ITCZ (Mitchell and Wallace 1992), with a blanket of large solar cloud forcing over nearly all northern hemisphere sites during June-October and then maximum solar cloud forcing migrating equatorward during October-January. All fields show large solar cloud forcing south of 4°S in March consistent with formation of a short-lived Southern Hemisphere ITCZ.

The greatest solar cloud forcing extends from about 10°N to 2°N (from the deep convection of the ITCZ to the SST front). In contrast, the greatest longwave cloud forcing is found in the Southern Hemisphere, with maximum values found at 20°S during the latter half of the year when a stratus cloud deck often extends to the equator (Klein and Hartmann 1993). Periods of relatively clear skies (e.g. January-March north of 5°N, and near the equator) are seen in both solar and longwave cloud forcing (as near zero). Weakly negative longwave cloudforcing values are non-physical and represent errors in the buoy estimate.

While the four sets (buoy, ISCCP, NCEP2, ERA40) have many similarities, there are also some notable differences, which are apparent when the buoy cloud forcing is differenced from each of the other three products. In the comparisons shown in Fig. 5 and 6, the non-buoy fields are interpolated to the buoy sites, and the annual cycle is computed from the difference field. ISCCP cloud forcing is most similar to that based on the buoy measurements. At all latitudes, however, ISCCP solar cloud forcing is weaker, which, as will be discussed in section 4, appears to be because ISCCP downwelling solar radiation is too strong.

NCEP2 has the largest differences from the buoy solar cloud forcing. In particular, NCEP2 shows extremely high solar cloud forcing during December through June, consistent with a tendency for this analysis to include too much deep convection on the equator during the warm season. If used as boundary conditions for an OGCM, the NCEP2 solar cloud forcing would result in a cold SST bias. For example, the NCEP2 solar forcing error of over –100 Wm^{-2} would lead to a 7°C cold bias within 3 months, assuming a 30 m thick slab ocean mixed layer. Because this is the warm season when the cold tongue is weak, this solar cloud forcing bias would cause an unrealistically prominent and persistent cold tongue. On the other hand, in the stratus cloud deck region at 20°S and north to the equator during the cold season, NCEP2 solar cloud forcing bias is of the opposite sign, which would tend to produce a warm bias in SST.

ERA40 solar cloud forcing exhibits smaller errors than NCEP2 near the equator during the warm season, presumably due to more realistic treatment of the frequency and character of deep convection. However, presumably due to insufficient meridional resolution, ERA40 has large errors (more than 60 Wm^{-2}) in the frontal zone when the cold tongue is well developed. Elsewhere, ERA40 and NCEP2 products have errors in solar cloud forcing with similar latitudinal and seasonal distributions.

The various longwave cloud forcing fields compared more favorably than their counterparts for solar cloud forcing. Although deviations from the buoy values were typically less than ± 20 Wm^{-2}, a few patterns can be seen in Fig. 6: All three non-buoy fields show positive deviations during January-June, and negative deviations during July-December. Part of the positive deviations during January-June are likely due to the weakly negative buoy values, which are non-physical and within the error estimates of the buoy measurements. In contrast, the negative deviations during July-December imply that the buoys observed more longwave radiation emitted from the clouds. This is consistent with low-level cloud coverage being underestimated in the three non-buoy fields during July-December.

b. Cloud forcing diagnostics

Because emission of longwave radiation by clouds is strongly dependent on temperature, different cloud types have a different ratio of solar to longwave cloud forcing. The subcloud water vapor concentrations also affect IR flux more than solar flux; thus, conditions with similar cloud base heights may have different IR forcing. More humid boundary layers will tend to have lower IR cloud forcing (Stephens and Webster 1981). Thus, to diagnose the radiative properties across the stratus deck/cold tongue/ITCZ complex, the ratio of CFRl/CFRs is computed for six different regions. These regions are as follows: stratus deck (~20°S, 85°W), southern (9°S-3.5°S), cold tongue (3.5°S-1°N), frontal (1°N-6.5°N), ITCZ (6.5°N-11°N) and northeast Pacific warm pool (11°N-13°N). Further, for each region, scatter plots of CFRl versus CFRs are shown for months when the region had significant rainfall, as determined by the TRMM rainfall product, and months when the region had no significant monthly averaged rain. Significance was determined based upon the error level provided by TRMM product. In order to provide a benchmark for models, the slope and intercept of the least-squares straight line fit to the buoy CFRl to CFRs scatter is shown in Tables 1 and 2.

As shown in Figs. 7 and 8, the slope of longwave to solar cloud forcing is closest to –1 in the cold tongue, southern, and stratus deck regions under non-precipitating conditions. Note that a value of –1 implies that IR and solar cloud forcing cancel and there is no net effect of clouds on the surface energy budget. The flattest slopes (indicating clouds that have marginal effect on downwelling longwave radiation, but are relatively opaque to solar radiation) were in the ITCZ region and the Southern Hemisphere region under significant rainfall. The most dramatic discrepancy is in the cold tongue region, where NCEP2 clouds have ITCZ-type radiative properties rather than Southern Hemisphere stratus deck (closer to –1) properties. It is important to note, though, that none of the regions had 1-1 CFRl/CFRs cloud properties. Longwave cloud forcing is always less than the solar cloud forcing for all regions in this study.

The relative effectiveness of clouds to emit longwave radiation and transmit solar radiation depends not only on the type of cloud forming (which can be characterized by its cloud base and cloud top height, and optical depths), but also upon the background emission and transmission properties of the lower troposphere. For example, longwave cloud forcing tends to be weaker in a moist region than in a dry region, all else being the same. During April of each year, NCEP2 humidity sections (Fig. 9) differ significantly from the observed counterparts (Fig. 10). These errors appear to be related at least in part to errors in the winds. For example, during April 2000 the sounding section indicates a double ITCZ while its counterpart from NCEP2 indicates a single primary ITCZ.

As shown in Figs. 5 and 6, solar cloud forcing discrepancies were larger than longwave cloud forcing discrepancies. Because cloud forcing depends upon a modeled estimate of the expected radiation under clear skies, errors in the modeled clear-sky radiation could bias the solar cloud forcing estimate. As shown in Figs. 11, the solar clear-sky radiation in ISCCP and NCEP2 have a seasonal cycle that differs from the buoy's, resulting in a 10 Wm^{-2} amplitude seasonal cycle in the difference field. It is likely therefore that the discrepancies between the buoy and non-buoy solar clear-sky radiation are due to the seasonal cycle of these values. It is uncertain, however, if they are modeled better in the buoy or non-buoy fields. The error due to the clear-sky solar model, although less than $\pm 10\ \mathrm{Wm}^{-2}$, could account for part of the discrepancy between the buoy and ISCCP solar cloud forcing. However, the important point is that clear-sky discrepancy is small when compared to the differences of 20-100 Wm^{-2} between the buoy and NWP solar cloud forcing. Hence the principal sources of the error in the NCEP2 cloud forcing appear to be specification of cloud type and coverage, and location of the ITCZ.

4. Reducing biases

Based upon the analyses in Section 3, ISCCP had the best comparison with the buoy cloud forcing measurements. However, the comparison did show systematic biases in the ISCCP solar cloud forcing field. While it is possible that there are errors in the buoy estimate of clear-sky solar radiation, it is unlikely that this would account for the positive bias in the ISCCP solar cloud forcing field. Rather, it appears that the discrepancy is in the full-sky downwelling solar radiation. ISCCP solar radiation is too strong, and would lead to a warm SST bias if applied to an OGCM.

A simple "fix" is to remove the mean bias (11 Wm^{-2}) from the ISCCP downwelling full-sky solar radiation. Alternatively, the bias could be modeled in terms of the full-sky solar radiation:

$$\text{Corrected } Rs = (1-f) * Rs \qquad (3)$$

This simple correction has the largest correction when there are no clouds present. If clouds were the source of error, then an alternative strategy would be to model the correction as a scale of the cloud effect:

$$\text{Corrected } Rs = Rs - f*CFRs \qquad (4)$$

In contrast, this bias correction is largest when the skies are cloudy. To determine the scale factor *f*, we assume *f* is a constant and insist that the corrected solar radiation co-located with buoys have the same mean solar radiation averaged over all sites as the buoys. For the ad hoc correction based upon solar radiation (3), *f* is 0.04; for the ad hoc correction based upon solar cloud forcing (4), *f* is –0.18. A comparison of these modeled biases and measured deviation are shown in Fig. 12. All three schemes are statistically equivalent.

5. Summary and Conclusions

The buoy cloud forcing fields were compared to three of the most commonly used global atmospheric products: satellite based ISCCP fields, NCEP2 reanalysis, and

ECMWF Re-Analysis (ERA40) fields. Of these, NCEP2 had the worst comparison, with large deviations implying a cold bias. The bias is particularly large (more than 100 Wm^{-2}) near the equator cold tongue during the warm season (February-April), when the cold tongue normally weakens. Persistently cold SSTs along the equator (i.e. a persistent cold tongue) would be expected to have important ramifications on the seasonal cycle in the entire eastern tropical Pacific.

The best comparison with the buoy-based cloud forcing was with the ISCCP data set. ISCCP solar radiation however was stronger than the buoy measured solar radiation at all sites throughout the entire overlapping period. It appears that this bias is due to errors in the ISCCP product, although it is beyond the scope of this paper to identify the cause. Until an updated scheme is released, users of the ISCCP solar radiation field may wish to do an ad hoc fix. Three schemes were presented: the simplest fix was to remove a mean bias of 11 Wm^{-2} from the downwelling solar radiation. The second scheme was to scale the solar radiation by a constant. A slightly more elaborate fix was to reduce the downwelling solar radiation by a scale value of the solar cloud effect. The choice of corrections depends upon the source of error. Corrections using scheme (3) are largest when the skies are clear, while corrections using scheme (4) are largest when the skies are cloudy. Users of these ad hoc corrections should understand their implications.

Longwave cloud forcing comparisons were better than for solar cloud forcing; deviations were typically less than 20 Wm^{-2}. Longwave cloud forcing appeared to be too strong in the ITCZ for all three products. Likewise, in the Southern Hemisphere, longwave cloud forcing appeared to be too strong during the warm season (January through June), and too weak during the cold season, when a stratus cloud deck typically develops.

The in situ measurements from buoys on which the present study was based can be used to validate NWP and satellite products. Linear fit polynomials for relating surface solar and longwave cloud forcing are shown in Table 1. These empirical relations can be used as a ground truth test for atmospheric models that generate their own cloud and surface radiation fields.

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List of Tables

Table 1. Solar (CFRs) and longwave (CFRl) cloud forcing statistics for rainy conditions. Uncertainties in the mean are at the 95% confidence limit. Statistically significant cross-correlations at the 95% confidence limit are indicated by bold.

	CFRs			**CFRl**			**CFRl = P1 * CFRs + P2**			**CFRs vs CFRl**
Region	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**P1**	**P2**	**Rms**	**Rxy**
WP	-182	-45	-133± 16	-2	31	14± 4	-0.09	1.0	8	-0.4
ITCZ	-185	-26	-96± 12	-11	20	4± 2	-0.12	-6.7	5	**-0.7**
Frontal	-159	-28	-107± 5	-2	51	23± 2	-0.28	-8.1	10	**-0.5**
CT	-108	-16	-45± 8	-13	38	3± 7	-0.42	-16.7	7	**-0.8**
South	-128	-34	-76± 11	4	15	10± 2	-0.06	5.4	3	**-0.3**
Stratus	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 2. Solar (CFRs) and longwave (CFRl) for dry conditions. Uncertainties in the mean are at the 95% confidence limit. Statistically significant cross-correlations at the 95% confidence limit are indicated by bold.

	CFRS [Wm^{-2}]			CFRL[Wm^{-2}]			CFRL = P1 * CFRS + P2			Cfrs vs cfrl
Region	Min	Max	Mean	Min	Max	Mean	P1	P2 [Wm^{-2}]	Rms [Wm^{-2}]	Rxy
WP	-139	-18	-49± 17	-6	38	14± 10	-0.29	-1.1	11	**-0.6**
ITCZ	-45	-16	-27 ± 8	-9	1	N/A	N/A	N/A	N/A	N/A
Frontal	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CT	-131	-31	-72± 8	-1	39	25± 4	-0.49	-7.4	5	**-0.9**
South	-124	-37	-80± 8	3	51	31± 5	-0.54	-14.1	5	**-0.9**
Stratus	-155	-68	-103± 8	24	66	48± 4	-0.35	11.9	7	**-0.8**

List of Figures

Fig. 1. EPIC mooring array shown in relation to April 2000 (lower panel) and October 2000 (upper panel) TRMM Microwave Imager (TMI) sea surface temperature (SST), TRMM rain rate, and QuikSCAT surface winds. Diamonds indicate TAO buoys. Large diamonds indicate EPIC-enhanced 95°W TAO buoys. The Woods Hole IMET buoy is indicated by a large square.

Fig. 2. Monthly averaged TMI SST (upper panel) and rainfall (lower panel) along 95°W from 8°S to 12°N and at 20°S 85°W.

Fig. 3. Monthly averaged solar cloud forcing at the surface along 95°W from 8°S to 12°N and at 20°S, 85°W from buoy measurements (upper left), ISCCP (upper right), NCEP2 reanalysis (lower left), and ECMWF operational (lower right). Solar cloud forcing is defined by (1) and has units Wm^{-2}.

Fig. 4. Monthly averaged longwave cloud forcing at the surface along 95°W from 8°S to 12°N and at 20°S, 85°W from buoy measurements (upper left), ISCCP (upper right), NCEP2 reanalysis (lower left), and ECMWF operational (lower right). Longwave cloud forcing is defined by (1) and has units Wm^{-2}.

Fig. 5. Mean annual cycle of solar cloud forcing field along 95°W from 8°S to 12°N and at 20°S, 85°W from buoy measurements (upper left), and mean annual cycle of difference between surface solar cloud forcing and buoy field along 95°W from 8°S to

12°N and at 20°S, 85°W; for ISCCP (upper right), NCEP2 reanalysis (lower left), and ECMWF operational (lower right).

Fig. 6. As in Fig. 5, but for surface longwave cloud forcing.

Fig. 7. Scatter plots of monthly-averaged longwave cloud forcing versus solar cloud forcing for precipitating clouds in six latitudinal bands defined as north east Pacific warm pool (11°N-13°N, 95°W), ITCZ (6.5°N-11°N, 95°W), frontal (1°N-6.5°N, 95°W), cold tongue (3.5°S-1°N, 95°W), southern (9°S-3.5°S, 95°W), and stratus (21.5°S-18.5°S, 85°W). As shown in the legend in the lower left panel, buoy values are indicated by Δ, NCEP2 by +, ECMWF by ×, and ISCCP by o. The negative 1-1 line is indicated by a dotted line. The least-squares straight line fit of the buoy cloud forcing values is shown by a thick black line extending over the range of the buoy solar cloud forcing. Significant rainfall was determined by TRMM rainfall within each latitudinal bin.

Fig. 8. Same as Fig. 7 but for months with no significant rainfall.

Fig. 9. NCEP2 relative humidity and meridional wind sections along 95°W for months corresponding to TAO tender sounding sections. Relative humidity contour interval (CI) is 10%. Meridional wind zero contour is shown as a thick line.

Fig. 10. Sounding sections of relative humidity and meridional winds from 95°W TAO tender ship. Relative humidity CI is 20%.

Fig. 11. As in Fig 5, but for clear-sky solar radiation at the surface.

Fig. 12. ISCCP downwelling solar radiation relative to buoy measured field (upper left) and ad hoc models of this bias: ISCCP downwelling solar radiation scaled by 0.04 (lower left), ISCCP cloud forcing scaled by -0.18 (lower right). All fields have units Wm^{-2}.