Validation of Clear-Sky Fluxes for Tropical Oceans from the Earth Radiation Budget Experiment

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ABSTRACT

The existence and magnitude of a systematic bias in the clear-sky longwave fluxes from the Earth Radiation Budget Experiment (ERBE) is investigated. The bias is apparently introduced because the ERBE method for scene identification does not account for large zonal gradients in longwave absorption by water vapor. The ERBE fluxes are compared to fluxes calculated with a radiative transfer model from ship radiosonde measurements. The comparison is based upon an analysis of 5 yr of coincident satellite and radiosonde observations for equatorial ocean regions. The differences between the ERBE and model fluxes are examined as functions of sea surface temperature (SST) and relative humidity. The authors use height-mean relative humidity $\overline{\mathrm{RH}}$ as an index of atmospheric moisture. The average offset between the model and ERBE fluxes ranges between +2 and +6 W m^{-2} for SSTs above 295 K, and the gradients with respect to SST are nearly identical. However, the difference between the model and ERBE depends significantly on the tropospheric relative humidity. ERBE fluxes exceed model fluxes for $\overline{\mathrm{RH}}$ above 70%, and the maximum offset of +9 to +12 W m^{-2} is consistent with previous estimates. There are also indications that the clear-sky fluxes for $\overline{\mathrm{RH}}$ below 25% may be underestimated by about 10–15 W m^{-2}. Since extreme values of height-mean humidity are relatively infrequent, the net bias introduced in the ERBE monthly mean clear-sky fluxes is generally less than the systematic error in estimates of the instantaneous fluxes. These findings support earlier work on the coupling between SST and the atmospheric greenhouse effect, in particular the existence of a super greenhouse effect for oceans warmer than 300 K. Recent reports of much larger systematic differences are not supported by this analysis. The results indicate that comparison of GCM and ERBE clear-sky longwave fluxes will depend explicitly on atmospheric humidity.

1. Introduction

Radiative climatologies from satellite measurements are useful for understanding the nature and variability of the atmospheric energy budget. An accurate determination of the earth's radiation budget is also important for the development of general circulation models (GCMs) (Hartmann et al. 1986). One of the primary datasets has been developed through the Earth Radiation Budget Experiment (ERBE). A distinguishing feature of the ERBE dataset is the compilation of clear-sky longwave flux emitted to space. The clear-sky fluxes have been used to study the atmospheric greenhouse effect and the coupling between greenhouse absorption, sea surface temperature, and atmospheric water vapor (Raval and Ramanathan 1989). The greenhouse effect is the difference between the longwave emission from the surface and the top of the atmosphere. In symbolic form,

$$G_a = \epsilon\sigma T_s^4 - F_a^+, \qquad (1)$$

where T_s is the surface temperature, ϵ is the surface emissivity, and F_a^+ is the clear-sky longwave flux. Subsequent work has focused on the relationship between G_a and tropical convection (Hallberg and Inamdar 1993; Inamdar and Ramanathan 1994). The clear-sky data are also critical for estimating the radiative effect of clouds, or cloud forcing, from satellite observations. The spatial and temporal variability of cloud forcing and the simulation of the cloud radiation fields by GCMs have been extensively validated against the ERBE cloud forcing data (e.g., Kiehl and Ramanathan 1990; Soden 1992).

As Slingo and Webb (1992) have noted, it is important to identify the sources of error in the available earth radiation datasets. Validation of GCM parameterizations against observations is predicated upon the accuracy of these observations. If there are large systematic errors in the satellite measurements, these errors could mask problems in the model physics. Some of the components of regional radiation budgets are comparable to the measurement uncertainty. For example, the net cloud forcing over much of the tropical oceans is much smaller than the individual longwave and shortwave cloud forcing terms (Ramanathan et al. 1989). Both the magnitude and sign of the net cloud effect could change with the introduction of small sys-

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tematic errors in convective regions. Harrison et al. (1990) have extensively reviewed the known error sources in the ERBE radiation data. The uncertainty in F_a^+ is contributed primarily by instrumental errors, incomplete diurnal sampling, and the space–time-averaging model. Harrison et al. conclude that the rms uncertainty in the monthly mean values is approximately 2 W m^{-2} with a systematic positive offset of 3–4 W m^{-2}. Using a stringent selection criterion for clear-sky data, Ramanathan et al. (1989) estimate an upper bound of 5 W m^{-2} on the rms error.

However, there have been several reports of systematic errors in the ERBE estimates of F_a^+ in regions of deep tropical convection. The existence and magnitude of the errors over tropical oceans are the subject of this investigation. Hartmann and Doelling (1991) suggest that a positive offset in ERBE data is introduced by the probabilistic technique used to identify regions of clear sky. Since the ERBE scene-identification method is based upon zonal flux averages, clear scenes with longwave emission well below the zonal-mean value may be mistakenly classified as cloudy. This erroneous classification is supposedly quite frequent over regions of deep convection with enhanced mid- and upper-tropospheric humidity and larger greenhouse absorption. The relatively large size of the ERBE scanner field of view also limits the number of clear-sky observations in broken cloud fields. Kiehl and Briegleb (1992) have calculated F_a^+ over tropical oceans using a radiative transfer model (Briegleb 1992) and European Centre for Medium-Range Weather Forecasts- (ECMWF) analyzed fields of temperature and humidity. Their comparison of the calculated fluxes with coincident ERBE observations suggest that the monthly mean ERBE fluxes may be overestimated by as much as 10–15 W m^{-2} in regions of deep convective activity. However, the relationship between globally averaged gradients in F_a^+ and T_s is not affected by the bias, a point to which we return in section 2. Recently, Hartmann et al. (1992) have derived estimates of F_a^+ that are smaller than ERBE by as much as 30 W m^{-2} in the west Pacific warm pool.

There is also evidence that the bias, if it exists, is either negligible or comparable to other sources of error. Inamdar and Ramanathan (1994) have compared model fluxes calculated from five years of ship radiosonde profiles with ERBE measurements and do not find a significant bias in the ERBE data. Approximately 56% of the soundings were made over warm oceans with $T_s \geqslant 300$ K, and 25% of the soundings are within 10° of the equator. While the rms difference for individual soundings is 9 W m^{-2}, the mean difference averaged over all the soundings is only 0.5 W m^{-2}. In another simulation study, Slingo and Webb (1992) have calculated the clear-sky radiation field over the oceans using atmospheric temperature and humidity from the ECMWF operational analysis. The simulated fluxes are roughly 3–4 W m^{-2} less than the ERBE fluxes for most of the Tropics. The magnitude of the differences is similar to the small positive bias suggested by Harrison et al. (1990).

Given the importance of accurate earth radiation budget data for climate studies, the frequency and magnitude of any systematic error should be firmly established. If the largest bias estimates are correct, much of the analysis of ERBE data for tropical regions would require substantial revision. In section 2, we compare ERBE data with model fluxes calculated from ship radiosonde profiles. The results establish the relation between the bias, sea surface temperature, and height-mean relative humidity and confirm that there is a positive bias in the instantaneous ERBE fluxes for warm moist atmospheres. There is also evidence for a bias of opposite sign when the height-mean humidity is below 25%. The net effect of the systematic error on monthly mean fluxes is determined by the relative frequency of moist and dry conditions. In section 3, we show that it is unlikely the offset is as large as some recent estimates. Our results are consistent with a small or statistically insignificant systematic error for most of the monthly average data.

2. Comparison of ERBE and model fluxes for warm ocean regions

a. Procedure and data

The method adopted for testing the clear-sky data is based upon a comparison of the ERBE fluxes with radiation model calculations. The model fluxes are derived using atmospheric profiles of temperature and humidity collocated with the ERBE observations. Inamdar and Ramanathan (1994) developed this approach to study the relation of G_a and tropical deep convection and showed the general statistical agreement of the model and ERBE fluxes. In the present paper, the relationship between the model and ERBE results are examined in greater detail as a function of sea surface temperature and atmospheric humidity.

The atmospheric profiles have been measured with radiosondes launched from ships. The tropical soundings used in this study are taken from the upper-atmospheric archive developed by the National Meteorological Center. The set of soundings is a subset of the data used by Inamdar and Ramanathan (1994) and includes all the profiles from 1985 to 1989 within 20° of the equator. The soundings have been carefully screened for internal consistency, and questionable soundings have been eliminated from the sample. Soundings terminating at pressures above 250 mb have also been removed from the sample dataset. Due to the uncertain performance of individual humidity sensors at low temperatures and relative humidities (Elliot and Gaffen 1991; Gutzler 1993), the McClatchey tropical atmosphere is substituted at pressures between 1 and 250 mb, and RH(p) is set to 0% for $p < 1$ mb. Sea surface temperatures are obtained from ship measurements made the same day as the sounding within a 2° radius of the radiosonde launch point.

The model clear-sky fluxes are calculated from the sounding profiles of temperature, pressure, and humidity using the Lowtran 7 radiative transfer model (Kneizys et al. 1988). Absorption by the water vapor continuum and present-day distributions of carbon dioxide, ozone, methane, and nitrous oxide have been included. The uncertainty in the calculations of F_a^+ relative to line-by-line results is approximately 3 W m^{-2} (Ellingson et al. 1991). The use of a fixed vertical distribution of RH(p) for $p < 250$ mb does not appreciably affect the calculated fluxes. For example, if RH(p) is varied from 10% to 100% for $1 \leqslant p < 250$ mb in the McClatchey profile, F_a^+ decreases from 294 to 290 W m^{-2}. Thus, the error in the model calculations introduced by the use of a climatological profile of humidity in the upper troposphere is approximately 4 W m^{-2}. There is still considerable uncertainty in the amount of absorption by the water vapor continuum. To estimate the corresponding uncertainty in the fluxes, all the calculations have been repeated using a 30% stronger continuum consistent with the Lowtran 6 model. The differences between the fluxes calculated with the Lowtran 7 and Lowtran 6 continuum coefficients are distributed about a mean of +2.3 W m^{-2} with a standard deviation of 1.4 W m^{-2}. This uncertainty is comparable to the other sources of error in the model fluxes.

The ERBE clear-sky fluxes are taken from the set of hourly averages for 2.5° × 2.5° regions or bins. Each sounding is assigned to a bin and matched with the nearest ERBE clear-sky measurement within a 24-h window centered on the time of the sounding launch. If no clear-sky conditions were detected by the ERBE scene-identification algorithm during this period, the sounding is omitted from the matched set. Since the ERBE scene identification is apparently biased toward dry conditions (Hartmann and Doelling 1991), the set of matched soundings also reflects that bias. However, the bias introduced in the model fluxes should be smaller than the systematic error introduced in ERBE. Since the soundings are launched under both clear and cloudy conditions, the distribution of model fluxes should include the effects of higher atmospheric humidity in partly cloudy regions. In addition, the tolerances in the spatial collocation, approximately the width of an ERBE bin, allow considerable variation in local atmospheric conditions within each geographic bin. The relationship between F_a^+ and height-mean relative humidity is not significantly affected by the matching process (section 2b).

To identify any systematic errors associated with deep convection, one needs some simple criteria to distinguish measurements from convective and nonconvective conditions. Several studies have established that the frequency of convection is related to T_s and that there is a climatological threshold temperature T_c for deep convection close to 300 K (Graham and Barnett 1987; Waliser and Graham 1993; Zhang 1993). The frequency of convection increases rapidly with T_s for T_s less than or equal to 303 K but decreases sharply for T_s greater than 303 K. Therefore, we first consider the difference between ERBE and the model calculations as a function of T_s.

In turn, deep convection tends to increase the amount of water vapor in the middle-to-upper troposphere (Rind et al. 1991). The mechanisms responsible for this increase include irreversible mixing driven by convection and the evaporation of cirrus anvils (Sun and Lindzen 1993). The additional vapor acts as a greenhouse gas, reducing the outgoing longwave radiation emitted to space. The signature of the increased humidity should be evident in the satellite observations. We also examine the difference between ERBE and model fluxes as a function of height-mean relative humidity denoted by $\overline{\mathrm{RH}}$. The fluxes actually depend on the vertical distribution of water vapor but $\overline{\mathrm{RH}}$ is a convenient index for distinguishing moist and dry conditions. The height-mean humidity is superior for this purpose compared to other measures of atmospheric vapor content—for example, column-integrated water vapor W—for several reasons. First, W and T_s are significantly correlated over tropical oceans ($r = +0.65$ to $+0.8$) because of the Clausius–Clapeyron relation and therefore cannot be treated as independent predictive variables for F_a^+ (Raval and Ramanathan 1989; Raval et al. 1994). On the other hand, $\overline{\mathrm{RH}}$ and T_s are not significantly correlated, and variations in $\overline{\mathrm{RH}}$ generally follow large-scale patterns of ascent and subsidence. Second, upper-tropospheric humidity is given greater weight in $\overline{\mathrm{RH}}$ than pressure-weighted means of relative humidity (Thompson and Warren 1982). Sharp increases in the upper-level humidity are found in tropical soundings and can significantly reduce F_a^+ (Inamdar and Ramanathan 1994). Third, $\overline{\mathrm{RH}}$ explains significantly more of the variance in F_a^+ than other measures of atmospheric vapor content (Raval et al. 1994). The average humidity is calculated for each sounding using

$$\overline{\mathrm{RH}} = \frac{1}{H}\int_0^H \mathrm{RH}(z)\,dz, \qquad (2)$$

where $H = 12$ km. The relative humidity in the integral is assumed to vary linearly between mandatory reporting levels in each sounding. The pressure measurements have been converted to altitudes using the standard McClatchey tropical atmosphere. To a good approximation, $\overline{\mathrm{RH}}$ is the average humidity in the first 12 km of the atmosphere. Raval et al. (1994) have used a similar measure of $\overline{\mathrm{RH}}$ to characterize the dependence of F_a^+ on T_s and $\overline{\mathrm{RH}}$. They find that the average flux is determined by these variables up to a standard error of roughly 5 W m^{-2} when T_s is greater than 298 K. The small error indicates that $\overline{\mathrm{RH}}$ is a useful parameter for examining the relationship between longwave flux and atmospheric humidity. In this application, $\overline{\mathrm{RH}}$ will be used to bin the differences between the calculated and measured estimates of F_a^+.

b. Results

The differences between the model and ERBE F_a^+ have been determined by averaging the matched model and ERBE fluxes for 1 K bins in T_s. The difference between the mean fluxes is shown in Fig. 1 as a function of T_s. The difference between the model and ERBE fluxes is approximately +2 to +6 W m^{-2} for T_s greater than 295 K. While the magnitude of this offset is comparable to the errors in the instantaneous fluxes, the differences are statistically significant for T_s greater than or equal to 299 K. The probability that the offset is due to random chance has been estimated using the pairwise Student's t-test. The probability is greater than 10% for SST below 299 K but is less than 1% for higher surface temperatures. There is no apparent evidence of a positive bias in the ERBE clear-sky fluxes for T_s greater than 300 K, the climatological threshold for deep convection. In fact, the model calculations are larger than the ERBE fluxes by approximately 3 W m^{-2} over the warmest ocean regions. Since most of the ship observations are within 3 K of T_c (Fig. 2), the transition to the climatologically convective regime should be adequately sampled.

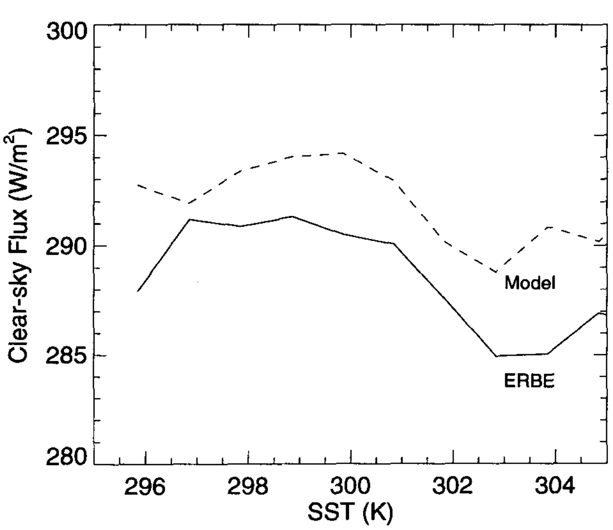

FIG. 1. Mean F_a^+ with T_s for 1985–1989. Solid line: ERBE; dashed line: model calculations from coincident ship soundings. Fluxes are averaged over 1 K intervals.

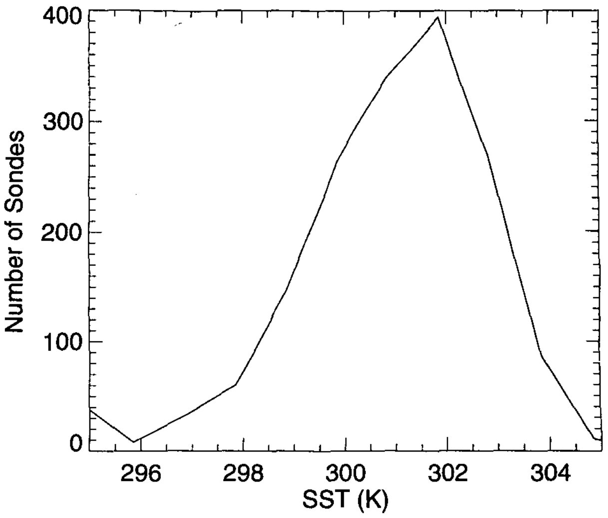

FIG. 2. Number of ship soundings matched with ERBE observations as a function of T_s for 1985–1989. The total number of soundings is 1658.

The mean fluxes have a broad maximum within 1 K of T_c in both the observations and the model (Fig. 1). Between 300 and 303 K, the two estimates of F_a^+ decrease with increasing T_s. The reduction in both the ERBE and model fluxes is 6.4 W m^{-2}. The peak in the clear-sky longwave emission near T_c occurs because G_a increases with SST faster than the surface blackbody emission (Ramanathan and Collins 1991). As a result of this super greenhouse effect, the clear-sky flux decreases with increasing SST. The rapid increase in greenhouse absorption above T_c is associated with moistening of the middle and upper troposphere by deep convection (Hallberg and Inamdar 1993; Inamdar and Ramanathan 1994). The agreement in the decrease in ERBE and model F_a^+ indicates that the seasonal and interannual relation between F_a^+ and T_s derived from the ERBE data is not affected by systematic errors. As Kiehl and Briegleb (1992) have shown, radiative transfer models reproduce the onset of the super greenhouse effect at T_s approximately equal to T_c and its derivative with respect to T_s derived from ERBE.

The difference between the ERBE and model fluxes as a function of height-mean relative humidity is shown in Fig. 3a. The plot shows that the ERBE fluxes are consistently larger than the model calculations for $\overline{\mathrm{RH}}$ greater than 70%. The differences are statistically significant for all $\overline{\mathrm{RH}}$ except for the range where the mean fluxes intercept between 60% and 70%. The lowest average ERBE flux is approximately 280 W m^{-2}, while the lowest model flux is 270 W m^{-2}. This difference is similar to previous estimates of a 10–15 W m^{-2} systematic error in the ERBE data (Kiehl and Briegleb 1992). One can test the sensitivity of this offset to the method for selecting soundings for comparison with ERBE. It is possible that part of the difference is contributed by errors in the relative humidity measurements. Some of the radiosondes may have penetrated saturated layers that are probably associated with clouds. The humidity above the saturated layers may be overestimated due to condensation on the radiosonde instruments. This would increase the calculated

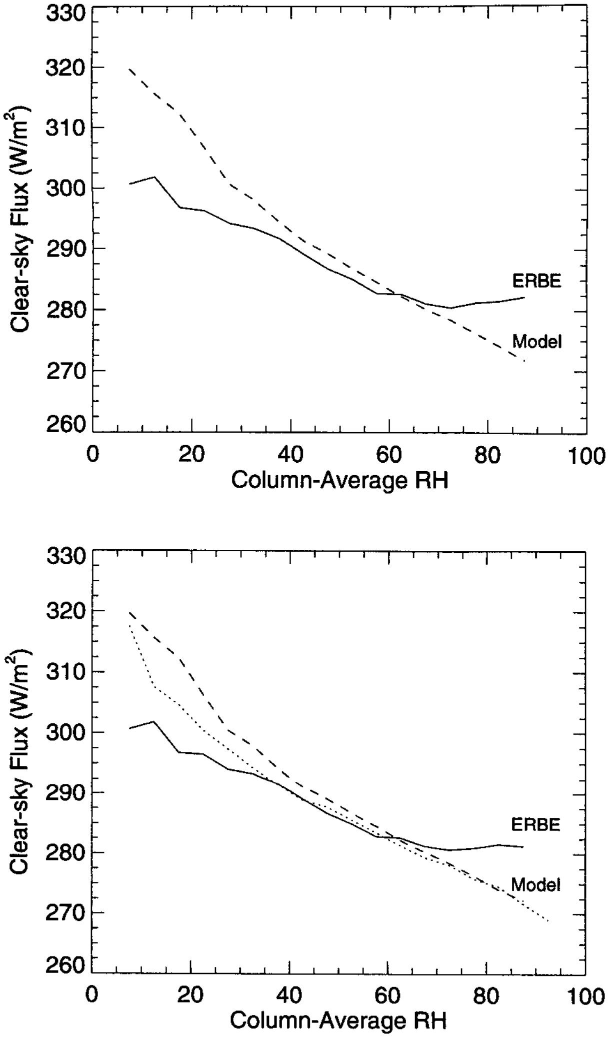

FIG. 3. (a) Mean F_a^+ as a function of height-mean relative humidity $\overline{\mathrm{RH}}$ for 1985–1989. Solid line: ERBE; dashed line: model calculations. Fluxes are averaged over intervals of 5% in $\overline{\mathrm{RH}}$. (b) Same as (a) excluding all soundings with RH(z) > 95% at one or more levels. Dotted line: average model F_a^+ for the complete (unmatched) set of 4380 ship soundings.

longwave absorption and would exaggerate the difference in the fluxes. The comparison of ERBE and model F_a^+ has been repeated in Fig. 3b using soundings with RH(z) less than or equal to 95% at all levels. The maximum offset between the ERBE and model F_a^+ for $\overline{\mathrm{RH}}$ greater than 85% is reduced by 1–9 W m^{-2}. On the other hand, the process of matching the soundings with ERBE clear-sky observations may lead to an underestimate of the offset. Since clear regions with high humidity are systematically omitted from the ERBE clear-sky sample, the corresponding soundings are also excluded. The relation of clear-sky flux to $\overline{\mathrm{RH}}$ has been recalculated using all the tropical soundings in the 5-yr dataset. As shown in Fig. 3b, the model F_a^+ at high relative humidity is changed by less than 1 W m^{-2}. These tests show that the uncertainty in the offset is in the range of 1–2 W m^{-2}. We conclude that the bias in the instantaneous ERBE fluxes grows linearly with $\overline{\mathrm{RH}}$ greater than 70% and reaches a maximum offset of 9–12 W m^{-2} at humidities close to saturation.

The difference between the model and ERBE fluxes at low relative humidities has not been previously observed. The estimates of F_a^+ from the model exceed the ERBE values by more than 10 W m^{-2} for $\overline{\mathrm{RH}}$ less than or equal to 25%. At present the origin of the discrepancy has not been determined. However, several explanations for the difference in F_a^+ have been examined and eliminated. The discrepancy may be caused by calibration errors in the humidity data for dry atmospheric conditions. Wade (1993) has reviewed several problems with the calibration and processing of low humidity measurements from radiosondes operated by the National Weather Service. A frequent practice has been to discount values of relative humidity below 20% and replace these values with the 20% threshold. The soundings in the present study have been screened for anomalous humidities introduced by these standard recording procedures (Gutzler 1993). In addition, the introduction of erroneously high humidities would tend to decrease, rather than increase, the model fluxes relative to the ERBE observations. It is unlikely that the discrepancy stems from errors in the radiative calculations that cannot be traced to errors in the radiosonde data. The known sources of uncertainty produce errors of less than 5 W m^{-2} in the model fluxes (section 2a). The difference cannot be explained by problems with the ERBE scene identification that account for the bias at $\overline{\mathrm{RH}}$ greater than 70%. Although there is a (zonally average) lower bound on the flux associated with clear-sky regions (Wielicki and Green 1989), there is no corresponding upper bound. It is also possible that the discrepancy is caused by cloud contamination in the ERBE clear-sky fluxes. However, this explanation is not consistent with the effects of the conservative clear scene identification at large $\overline{\mathrm{RH}}$. Diekmann and Smith (1989) have compared the amount of cloud cover derived from coincident ERBE and high-resolution Advanced Very High Resolution Radiometer observations over two regions in the eastern tropical Pacific and Atlantic Oceans. A small percentage of scenes with more than 5% cloud cover are incorrectly identified as clear, and the resulting errors in the longwave fluxes are generally negligible.

Despite the large differences between model and ERBE fluxes shown in Fig. 3, the rms differences averaged over 1985–1989 are approximately 0.5 W m^{-2} (Inamdar and Ramanathan 1994). The reason for the small rms errors is the low frequency of very dry and very moist soundings. The distribution of soundings has a broad maximum between 30% and 60% relative humidity (Fig. 4a). The integrated fraction of soundings with $\overline{\mathrm{RH}}$ less than R is plotted as a function of R

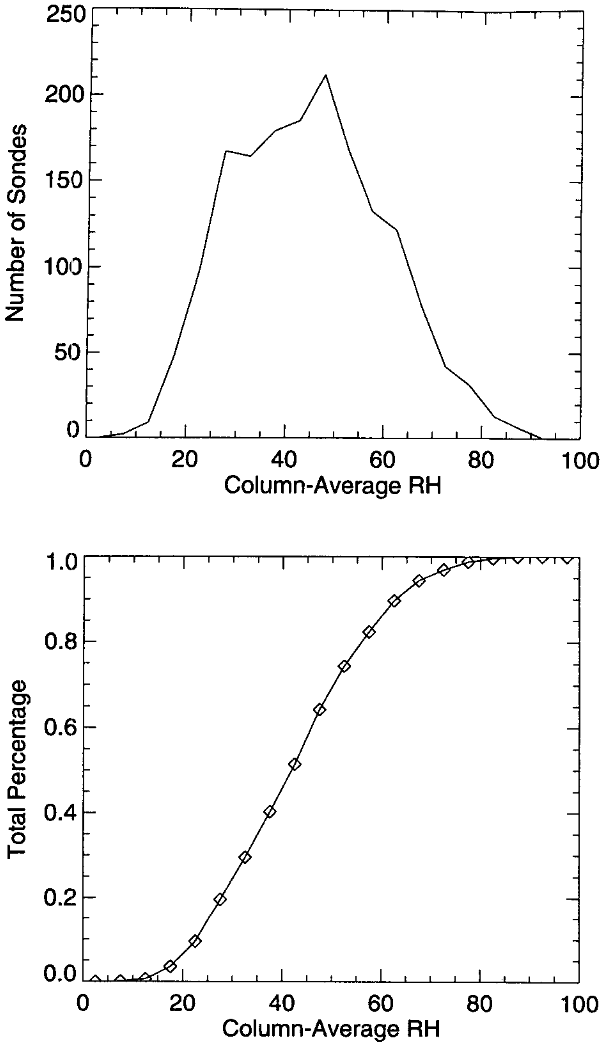

FIG. 4. (a) Number of soundings matched with ERBE observations versus $\overline{RH}$ for 1985–1989. The soundings are summed over intervals of 5% in $\overline{RH}$. (b) Fraction of soundings with $\overline{RH} \leqslant R$ versus R.

in Fig. 4b. Approximately 12% of the soundings have $\overline{RH}$ less than 25%, the range of humidities where the model exceeds ERBE by more than 10 W m^{-2}. Only 11% of the soundings have $\overline{RH}$ greater than 60%, where ERBE exceeds the model fluxes by up to 12 W m^{-2}. The differences between the model and ERBE at small and large humidities have opposite sign, and in general the net effect is comparable to random errors. The meridional averages of the ERBE and model fluxes are shown in Fig. 5. Since the soundings are not distributed uniformly in space or time, the averages are not intended to be climatologically representative. The two estimates of F_a^+ differ by less than 12 W m^{-2} in general and by less than 6 W m^{-2} in the west Pacific and Indian Oceans. The agreement in these convective regions may be explained by the frequent proximity of deep convection and large-scale subsidence. Thus, the net effect of the systematic errors on monthly fluxes for larger regions depends on the relative frequency of moist and dry conditions.

3. Lower limits on tropical clear-sky fluxes

There are alternative methods for deriving clear-sky fluxes that do not depend explicitly on clear-sky scene identification. The fluxes computed with these independent methods may be compared with ERBE to check for systematic biases through a process similar to the analysis in section 2. In the approach used by ERBE, each measurement is associated with clear or cloudy conditions. The clear-sky fluxes are averages of the individual clear-sky measurements weighted appropriately to account for diurnal variability. It is also possible to regress the observations against independent estimates of cloud amount. The clear-sky fluxes are then given in the limit of small or vanishing cloud cover (e.g., Ardanuy et al. 1989). The fluxes used in the regression method are mean values calculated by averaging all the observations. The estimates of cloud amount are obtained from other satellite data closely matched in space and time. One of the main factors limiting the accuracy of regression methods is the accuracy of the estimates of cloud amount. Reliable estimates of cloud cover are notoriously difficult to obtain, and in situ and satellite-derived cloud cover can differ significantly (Haskins et al. 1993). In regions with extensive cloud cover, the regression of flux against cloud amount may not give an accurate clear-sky intercept. In this section, we show that regression methods may significantly overestimate the bias in the estimates of F_a^+ from ERBE.

Ockert-Bell and Hartmann (1992) have developed a regression technique for determining the cloud ra-

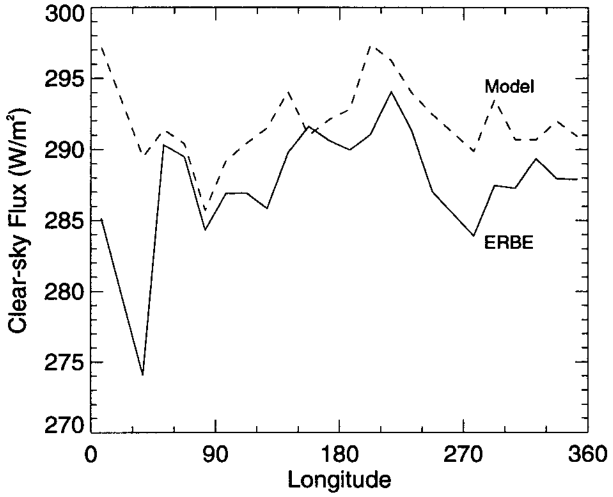

FIG. 5. Mean F_a^+ for matched observations from 1985 to 1989 averaged over 20°N–20°S and 15° of longitude. Solid line: ERBE; dashed line: model fluxes from ship soundings.

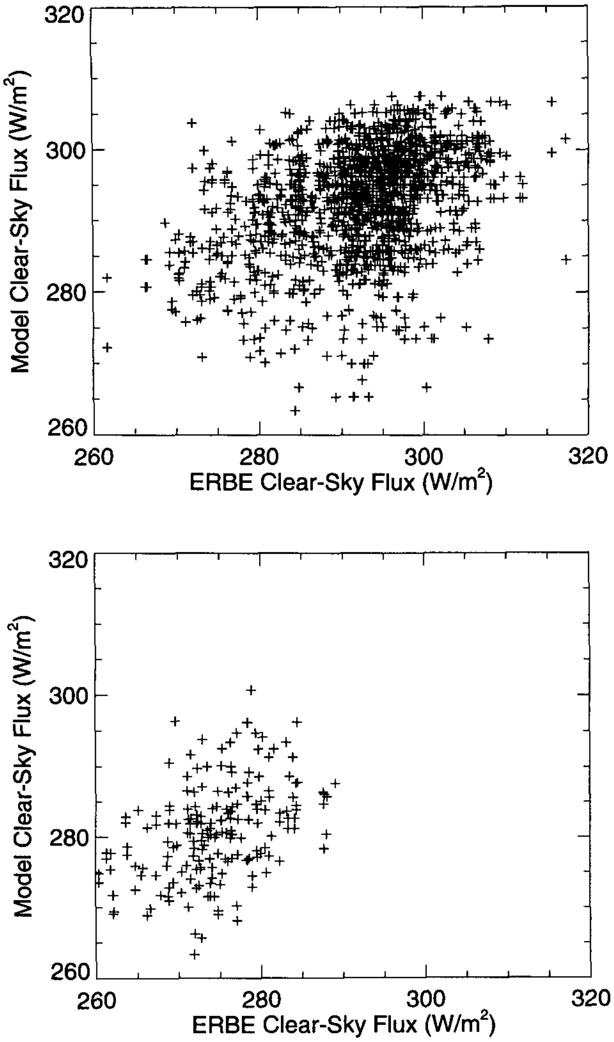

FIG. 6. Model F_a^+ calculated from soundings compared with coincident ERBE F_a^+. Each point represents a sounding matched with the closest ERBE clear-sky daily mean F_a^+ within a 12-h window for a 2.5° × 2.5° region containing the sounding. (a) Puerto Rico (Dec 1985–Feb 1986); (b) Singapore (Oct–Dec 1985).

diative forcing characteristic of different cloud types. The radiative fluxes are taken from ERBE, and the coincident cloud cover and cloud classification from the International Satellite Cloud Climatology Program (Rossow and Schiffer 1991). Two of the coefficients in the regression are associated with shortwave and longwave clear-sky fluxes. Hartmann et al. (1992) derive estimates of F_a^+ with this method that are up to 30 W m^{-2} below the corresponding ERBE fluxes for portions of the west Pacific warm pool. Hartmann et al. (1992) attribute this difference to a systematic error in the ERBE data for regions of deep tropical convection. They support this conclusion by calculating the zonal gradient in F_a^+ between Singapore and San Juan, Puerto Rico. These sites are located in regions of active and suppressed convection, respectively. If there is a systematic offset in the ERBE data for convective regions, the true gradient should be larger than the gradient in the ERBE fluxes. Using a radiative parameterization, Hartmann et al. (1992) find a 35 W m^{-2} difference in F_a^+ between Singapore and San Juan. The gradient in F_a^+ from ERBE between Singapore and nearby subsidence regions is only 10–15 W m^{-2}. The discrepancy between the ERBE and model gradients suggests that G_a in tropical convective regions is much larger than estimates derived from ERBE data. In this section, we examine the findings in Hartmann et al. (1992) to determine whether substantial revision of the ERBE clear-sky fluxes is required.

From the analysis of the ship soundings, the difference between ERBE and model fluxes approaches a maximum of 9–12 W m^{-2} at height-mean relative humidities close to saturation. To understand the discrepancy between the sounding and regression results, we have calculated the zonal gradient in F_a^+ between Singapore and Puerto Rico using the ERBE and model fluxes. The clear-sky fluxes are estimated using the model discussed in section 2 and radiosonde data from the NMC archive. Atmospheric profiles of temperature and humidity from October to December 1985 (Singapore) and December 1985 to February 1986 (San Juan) from the NMC archive are included in the sample dataset. Since all soundings are treated as clear regardless of the true cloud cover at the time of observation, the distribution of F_a^+ should reflect the enhanced atmospheric vapor content near convective clouds. The model fluxes are compared with coincident ERBE data in Fig. 6. Each point represents a sounding matched with the closest ERBE daily mean flux within a 12-h window for a 2.5° × 2.5° region containing the sounding. The average fluxes from the matched measurements for Singapore are 274.5 ± 0.4 W m^{-2} (ERBE) and 280.7 ± 0.4 W m^{-2} (model). For San Juan the averages are 292.2 ± 0.2 W m^{-2} (ERBE) and 292.6 ± 0.2 W m^{-2} (model). The uncertainty in these mean values reflects the distribution of the fluxes only and does not include instrumental errors. The average fluxes at the two locations differ by less than 6 W m^{-2}.

The agreement between the two estimates of F_a^+ is corroborated by comparing the fluxes from the complete (unmatched) sounding and ERBE datasets. The distribution of the model fluxes for all soundings from Singapore and Puerto Rico is shown in Fig. 7. The mean fluxes for Singapore and San Juan are 271.8 W m^{-2} and 293.6 W m^{-2}, respectively. The corresponding monthly mean ERBE fluxes averaged over the same periods for these locations are 267.7 W m^{-2} and 294.7 W m^{-2}, respectively. The model flux gradient of $\delta F_a^+ = 22$ W m^{-2} is quite similar to the ERBE estimate of $\delta F_a^+ = 27$ W m^{-2}.

The agreement between the model and ERBE indicates that the zonal flux gradients are not as large as

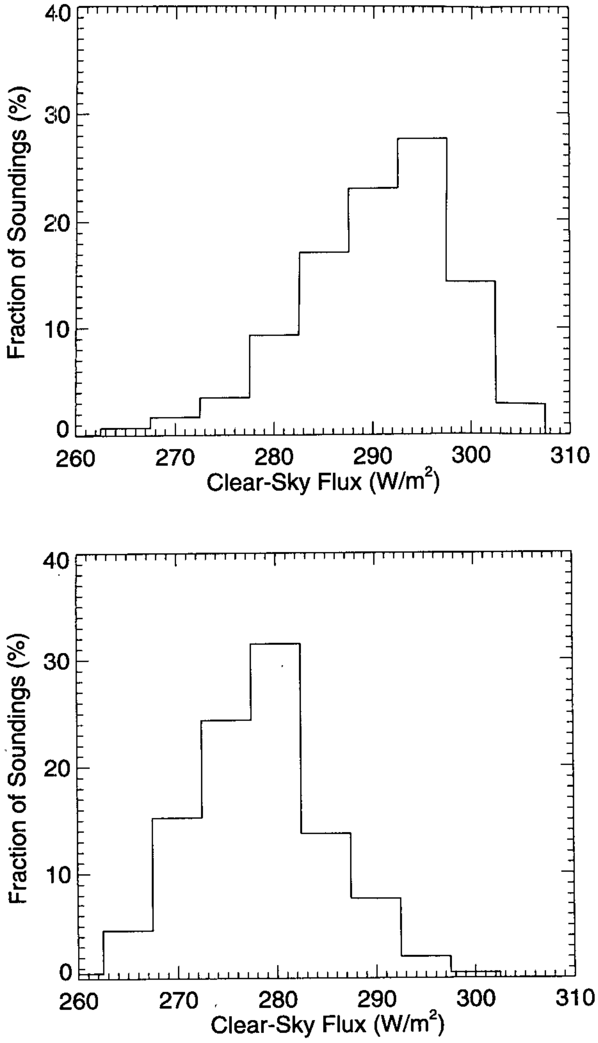

FIG. 7. Distribution of model F_a^+ calculated for all available soundings. (a) Puerto Rico (Dec 1985–Feb 1986); (b) Singapore (Oct–Dec 1985).

Hartmann et al. (1992) suggest. Hartmann et al. derive their estimate of $\delta F_a^+ = 35$ W m^{-2} using a formula for F_a^+ proposed by Thompson and Warren (1982, 1983). The Thompson–Warren parameterization is a function only of the surface temperature T_s and the height-mean relative humidity $\overline{\mathrm{RH}}$. There are systematic differences between the Thompson–Warren and model fluxes for the ship soundings matched with ERBE measurements. The two estimates of F_a^+ are plotted against $\overline{\mathrm{RH}}$ in Fig. 8. The Thompson–Warren estimates are consistently 8–18 W m^{-2} lower than the model values over the entire range of relative humidity. Since the parameterization is based upon an early version of Lowtran, the differences are probably due to improvements in the radiation code incorporated in more recent versions. Raval et al. (1994) found comparable differences between the Thompson–Warren parameterization and ERBE estimates of F_a^+ for tropical and subtropical areas. The agreement between the Lowtran 7 model and line-by-line codes (Inamdar and Ramanathan 1994) suggests that the Thompson–Warren parameterization may not be valid for most tropical regions.

The smaller zonal gradients call into question the bias estimates from the regression analysis. It is possible to place an upper limit on the systematic bias in ERBE fluxes by calculating a lower range of (instantaneous) F_a^+ for tropical oceans. The profile used to estimate F_a^+ is a standard McClatchey tropical atmosphere with T_s equal to 299.7 K and 99% relative humidity from the surface to the tropopause. Because the atmosphere is virtually saturated, the calculated greenhouse effect should be close to the maximum attainable trapping. The effects of increasing the lapse rate have been neglected since the temperatures above the planetary boundary layer are quite homogeneous (Wallace 1992). Changes in T_s alone would steepen the lapse rate in the boundary layer, but the enhanced greenhouse absorption is offset by higher surface emission (Hallberg and Inamdar 1993). The outgoing flux derived with the Lowtran 7 code is 264 W m^{-2}, which is 5 W m^{-2} less than the average model estimates of F_a^+ at high relative humidity (Fig. 3). Based on the distribution of $\overline{\mathrm{RH}}$ (Fig. 4), this analysis indicates that monthly mean values of F_a^+ below 260 W m^{-2} should occur very infrequently. This lower range for F_a^+ should be compared with the regression results for the warm pool (Hartmann et al. 1992, Figs. 7c,d). The estimate of F_a^+ from the regression is less than 260 W m^{-2} over significant portions of the Indian Ocean and west Pacific. As Hartmann et al. (1992) note, the regression may be inaccurate in convective regions with persistent

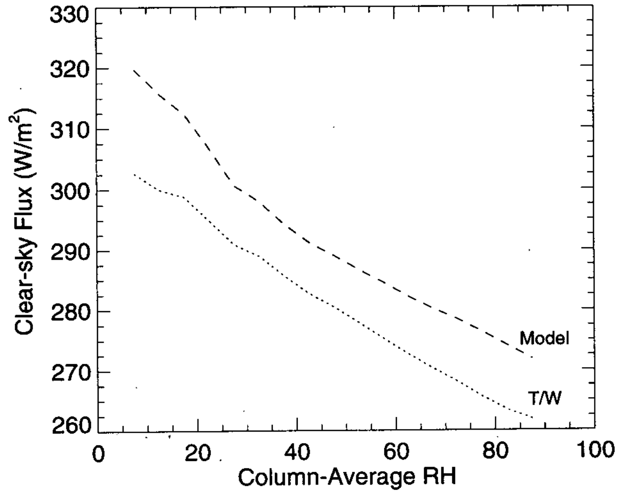

FIG. 8. Mean F_a^+ calculated from the Thompson–Warren parameterization and Lowtran 7 for the 1658 matched soundings from 1985 to 1989. Dotted line: Thompson–Warren; dashed line: Lowtran 7. Fluxes are averaged over intervals of 5% in $\overline{\mathrm{RH}}$.

cloud cover. The percentage of clear-sky observations is small, and the distribution of fractional cloud cover (the independent variable) is skewed toward overcast conditions. The low frequency of clear-sky observations also means that the average ERBE clear-sky fluxes may not be representative. However, the very low clear-sky flux in regions of deep convection from the regression analysis is not supported by the detailed model calculations.

4. Concluding remarks

This study has addressed the possibility of a large bias in the ERBE clear-sky longwave fluxes. The bias is supposedly introduced by spatial and temporal variability of atmospheric water vapor and uncertainties in the ERBE clear-sky analysis due to cloud contamination. This issue is significant in part because cloud-radiative forcing, an important climate diagnostic, is referenced to clear-sky fluxes. Cloud forcing estimates from ERBE and earlier instruments have been widely used in GCM validation studies. It is evident that a significant bias would probably invalidate most of the results for convective regions.

The satellite measurements have been compared with fluxes calculated with a radiation model initialized with tropical atmospheric profiles. This approach appears to be more reliable than regression methods, which do not give accurate estimates of F_a^+ in tropical regions with persistent extensive cloud cover. The differences between the satellite and model fluxes are a strong function of the atmospheric humidity but do not depend significantly on the sea surface temperature. The ERBE fluxes differ systematically from the model calculations at height-mean humidities above 70%. The difference between the estimates of F_a^+ grows linearly with humidity, and the maximum offset of approximately 9–12 W m^{-2} occurs close to saturation. There is also a previously unreported discrepancy at low humidities. Based upon these results, it appears that the validation of GCM clear-sky radiative calculations against ERBE should include height-mean humidity as an explicit discriminant.

However, the conditions for the largest differences occur infrequently in the radiosonde profiles. Since the differences between the fluxes have opposite sign at very low and very high humidities, the net effect is generally less than 10 W m^{-2} even in regions of deep convection. However, the sounding data is irregularly distributed in space and time. The differences between ERBE and model clear-sky radiation budgets may still be significant in regions of subsidence or active convection on monthly or seasonal timescales (Kiehl and Briegleb 1992). Nonetheless, we find no evidence that the difference frequently exceeds approximately 12 W m^{-2} in moist tropical regions. This result is consistent with maps of the flux differences developed by Slingo and Webb (1992) and Kiehl and Briegleb (1992) using global humidity fields derived from operational analyses.

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