BNL 61427
Informal Report

ANOMALOUS CLOUD ABSORPTION? A CRITIQUE OF THE PAPER ENTITLED "ABSORPTION OF SOLAR RADIATION BY CLOUDS: OBSERVATIONS VERSUS MODELS"

["Absorption Of Solar Radiation By Clouds: Observations Versus Models", by R. D. Cess et al., Published in Science 267, 496-499 (1995)].

D. G. Imre and E. Abramson
Environmental Chemistry Division
Brookhaven National Laboratory
Upton, NY 11973-5000

February 1995

UNDER CONTRACT NO. DE-AC02-76CH00016 WITH THE UNITED STATES DEPARTMENT OF ENERGY.

Introduction

In a recent paper R. Cess and co-authors (R.D. Cess et al., 1995) attempt to prove that general-circulation-models of the atmosphere do not correctly calculate short-wave absorption by cloudy skies. Co-located satellite and surface measurements are used to assess the relative effects of clouds on short-wave fluxes at both the top of the atmosphere and at the surface. The differences, expressed as average, Cloud-Radiative-Forcing (CRF) ratios, are evaluated both directly from measured fluxes (their Figure 1) and indirectly from plots of the Top-Of-Atmosphere (TOA) albedo against transmission (their Figure 2). The two different analyses are then connected *via* their equation 1.

Our study of the paper raised the serious concern that, due to unexamined uncertainties in their analyses, their final conclusions are not well founded. Herein, we give critiques of their two basic methods of analysis, refered to as "the slope" and "the direct CRF" methods.

In **Section I** we discuss the slope method and argue the following:

- **a.** Within the assumptions which are necessary to derive their equation 1, the cloud forcing ratio is completely determinable from clear-sky data alone.
- **b.** The assumption that the TOA albedo is linearly related to atmospheric transmission is particularly egregious.

In **Section II** we discuss the direct CRF method and argue the following:

- **a.** The method is based on small differences of large numbers and as such requires more care in the error analysis than has yet been demonstrated.
- **b.** The definition of "clear-sky" suffers from ambiguities. These ambiguities can lead to systematic errors on the order of the effect which is to be measured.

In **Section III** we present a previous analysis of some of the same data by several of the current authors. This analysis, which to our knowledge has never been retracted, is incompatible with the conclusions of the latest paper.

At the outset we would like to make it clear that we are not attempting to disprove the main thesis of this paper, that cloudy skies absorb more short-wave radiation than predicted by various models. What we find is that the data and analysis given in the paper do not support such a conclusion and, in fact, do not shed any new light on the subject.

All data herein derive from one of the four papers listed below*, or slides and lecture notes provided us by Professor R. Cess. Any numbers which appear here, other than those given explicitly in the sources, derive from our digitizations of figures contained in the same.

*[1] R. D. Cess, M. H. Zhang, P. Minnis, L. Corsetti, E. G. Dutton, B. W. Forgan, D. P. Garber, W. L. Gates, J. J. Hack, E. F. Harrison, X. Jing, J. T. Kiehl, C. N. Long, J.-J. Morcrette, G. L. Potter, V. Ramanathan, B. Subsilar, C. H. Whitlock, D. F. Young, and Y. Zhou, Science, 267, 496-499 (1995).

[2] S. Nemesure, R. D. Cess, E.G. Dutton, J.J. Deluisi, Z. Li, and H. Leighton, Journal of Climate 7 579-585 (1994)

[3] R. D. Cess, S. Nemesure, E.G. Dutton, J.J. Deluisi, G.L. Potter and J-J Morcrette, Journal of Climate 6 308-316 (1993)

[4] R. D. Cess, E.G. Dutton, J.J. Deluisi and F. Jiang, Journal of Climate 4 236-247 (1991)

I. THE SLOPE

The main argument of the paper is presented in Figure 2 where we find plots of TOA albedo (α_t) *vs.* transmission (T). In order to infer a relation between the slope ($-\beta$) and cloud absorption, the authors present Equation (1), relating the cloud forcing ratio (R) to the slope.

$$R = \frac{Cs(S)}{Cs(TOA)} = \frac{(1-\alpha_s)}{\beta} \qquad (1)$$

In this equation:

> Cs(S) and Cs(TOA) are "average" surface and TOA cloud-radiative-forcings, defined as the mean difference between "clear-sky" and "cloudy-sky" fluxes.
> α_s = surface albedo (in general a function of Solar Zenith Angle (SZA) and of cloud cover, here replaced by a constant equal to a diurnal average, for Boulder $\alpha_s = 0.17$).
> $-\beta$ is the slope obtained from a linear fit to a plot of TOA albedo *vs* transmission.

On the basis of Equation (1) smaller slopes are associated with larger cloudy-sky absorption. Since the slopes exhibited by the data (Figure 2a) tend to be ~25% lower than those predicted by the models (Figures 2b and 2c), "anomalous absorption" is inferred.

a) β is cloud independent

In Figure 2, data from all solar zenith angles and all degrees of cloudiness are plotted together and a straight line is fit to the entire set. Within this treatment there are two "drivers" for the transmission axis, one is cloud cover and the second is SZA, since a_t and T are functions of both. (For example the *clear-sky* transmission in Boulder changes from 0.82 at solar zenith to 0.59 at 72°, 30% of the total range, while α_t changes from 0.16 to 0.30 over the same range). If we accept that a linear representation is reasonable, which is the basis of Equation 1, we must then also accept the fact that the slope of this straight line can be determined completely by any two points on the line. As part of the data set, the clear-sky points, ($\alpha_t = 0.16$ $T = 0.82$) and ($\alpha_t = 0.30$ $T = 0.59$) for instance, must be on that line. (A derivation of Equation 1, given in Appendix 1, requires, explicitly, that the clear-sky points fall on the same line as all others.) Thus, within the linear approximation, the slope is completely determinable from clear-sky data only.

If, on the other hand, it is suggested that the slope as obtained from only the clear-sky data is significantly different from that obtained from the entire data set, the equation relating R to "the slope" is invalid and a comparison of slopes is not meaningful.

b) The linearity

The paradox discussed above is obviously in the assumption of linearity, which we examine in this section. In Figure 3 we plot two different data sets along with fits to various functional forms; there is so much scatter that it is difficult to decide whether a linear fit is appropriate. We don't know what causes this scatter; it may be experimental error, or the inclusion in one graph of many different solar zenith angles (the cloud forcing ratio has already been predicted by ECMWF to vary by a factor of 1.4 with solar zenith angle R. D. Cess et al. 1993). If we make the unsupported assumption that, whatever the cause of the scatter, it is in some fashion unimportant and may be ignored, then we may try to bin the data according to transmission. This was done for the Cape Grim and Samoa data by Prof. Cess (private communication, R. Cess) and we have treated the Boulder (ERBE) data similarly; the binned data are shown in Figure 4 with linear (Figure 4a) and quadratic (Figure 4b) fits. The binning removes much of the scatter and produces plots which suggest a curvature. As shown in Figure 5, the slopes of all three quadratic fits increase with cloud cover. This trend is repeated in all data sets examined, which leads us to believe that the local slopes as given by the quadratic fits are better representations of the data than are straight lines. The linear approximation, which is essential to the derivation of equation 1, would appear to be invalid, and thus using this equation to analyze the data introduces errors which have yet to be quantified.

To put it another way, the entire argument of the slope method rests upon the difference between the models' slope of -0.8 and the data's "slope" of -0.6, a 25% difference, while at the same time ignoring the fact that the true slopes may be changing by anywhere from a factor of two to a factor of seven. We note that while the choice of a quadratic fit is not motivated by physical reasoning, and is thus completely arbitrary, any other functional form which allows for a local slope will give similar results. The point is that the uncertainties quoted in the paper are only those which are given formally by least-squares fits of the data to postulated functional relationships; such uncertainties tell us little about the adequacy of these presumed relationships.

The authors themselves appear to recognize that for their argument to hold it is essential that slope be independent of cloud cover. In the manuscript originally submitted for publication (August, 1994) they took care to state explicitly that "When only the left-hand half of the data is considered, the resulting albedo slope (-0.598) is virtually identical to that for the complete data set." This assertion was dropped from the final draft and it is our understanding that the non-linearity is now accepted by the authors and is, furthermore, the subject of a new publication, in preparation. Despite this retraction of a major underpinning, the argument based on the "slope" was not altered.

If we accept the idea that a slope with magnitude smaller than that seen in the models (0.8) is indicative of an "anomalous absorption" then, with reference to Figure 5, we see that this occurs to the greatest extent in the clearest skies. The cloudiest skies, those with a transmission of less than 0.3 actually would show an anomalous *transmission* .

II. THE CLOUD FORCING RATIO

We have presented reasons to be leery of a derivation of CRF ratio from Equation 1. Although this method is preferred by R. D. Cess et al. (1995), another, the direct CRF method, is used in support of the primary argument.

The authors present Figure 1 in which they purport to show that the presence of clouds causes a "mean" increase of $63W/m^2$ reflected to TOA but a mean loss of $93W/m^2$ on the ground (both referenced to clear-sky). This difference implies a mean absorption of $30W/m^2$ due to clouds, or $R = Cs(S)/Cs(TOA) = 1.46$ while "theoretical models typically yield $Cs(S)/Cs(TOA) \approx 1$." Below, we examine this method and show that its associated uncertainties are larger than the effect reported.

a) Un-quantified errors

The reported mean cloud forcing, Cs(S)-Cs(TOA), of $30W/m^2$ is derived from differences between fluxes measured under clear and cloudy conditions. The variation of cloudy sky forcing ($600W/m^2$) is quite large with respect to this effect and even clear sky fluxes present day to day variations of comparable magnitude ($\pm 45W/m^2$). Two related problems arise. First, just random, statistical uncertainties can be comparable to the effect and should have been reported. Second, and more serious, the large fluctuations are capable of masking systematic errors which, small on the scale of the fluctuations, may be significant with respect to $30W/m^2$.

Systematic errors, which are often difficult to recognize, may result from many sources among them:

- biases in the reduction of satellite measured radiances to fluxes
- the sampling by surface pyranometers and satellites of areas (both surface and sky) which differ both in extent and location
- the determination and/or definition of clear-sky.

Several of these errors, in various forms, have been identified in R. D. Cess et al. (1991, 1993), but not quantified. Here, we concentrate on one, the definition of clear sky which is the first step in the calculation of cloud forcing.

b) Determining the clear sky limit

i) Clear Sky Is Not So Clear

The line of reasoning introduced in Figure 1 is based on differences between the cloudy-sky fluxes (TOA and surface) and the two corresponding references designated as clear-sky fits, or limits. The first question might be how well one can determine these clear-sky limits. To do this we rely on data reported in R. D. Cess et al. (1993) which is presented in Figures 6 and 7. Figure 6a is of TOA flux, and Figure 7a of surface flux, for all those points which were designated in the paper as representing clear sky; linear fits to the data are superposed. In order to better display the spread in this clear-sky data we show, in Figures 6b and 7b, the differences between the data and the derived clear-sky fits. As is now readily apparent, the root-mean-square deviation for each one of these plots is comparable to the cloud forcing effect, Cs(S) - Cs(TOA) reported in R. D. Cess et al (1995). This is not just a sampling problem which could be reduced by more extensive data collection. Rather, the optical properties of "clear sky", which vary with water vapor content, aerosols, surface moisture etc., are not sharply defined on the scale of the small differences we wish to measure. Our choice of what is considered clear-sky is unique only within the limits of this scatter or, with reference to Figure 6b, to within about $45W/m^2$. Thus, due to this problem alone, the uncertainty in the cloud forcing is larger than the measured effect of $30W/m^2$.

ii) Clear-sky limits by two different methods

In several papers (R. D. Cess, 1991, 1993, 1995), two basic methods have been used for the identification of "clear-sky" limits. The first is satellite based, scene identification. The second is an "upper envelope" method in which the data are displayed as in Figure 1, binned according to SZA, and then the top-most data point in each bin (designated as "clear-sky") is used in a straight line fit. This line is the clear-sky reference.

We examine the consistency between these two approaches, and thus the degree by which our clear-sky limit might be reasonably varied, by comparing their results for the same data set. Figure 8 shows the fit to clear-sky surface-insolation data, as determined by ERBE scene identification (R. D. Cess et al. 1993), and our own upper-envelope fit using the same (total) data set. We see that the two methods give results which differ by an average of $30W/m^2$. Compared with an average surface-insolation of $\sim 700W/m^2$ this is an agreeably small (4%) uncertainty; however, it is *not* small when compared with the supposed anomalous absorption. Since an uncertainty in the mean, clear-sky insolation translates directly into the same absolute uncertainty in the cloud forcing, the anomalous absorption might now be written as $30 \pm 30W/m^2$.

The effect of "broken-clouds" on the determination of clear-sky, surface flux is, as pointed out in R. D. Cess et al. (1993,1995), also a problem and also contributes to the uncertainty. Since in the "upper envelope" method, which was used for the data reduction in the 1995 paper, the clear-sky limit for TOA is chosen independently of that for the ground data the uncertainties in the two will be additive.

iii) Clear sky in the Cape Grim data set.

Figure 9 (courtesy of Prof. Cess) shows the Cape Grim data with Prof. Cess' fits to the clear-sky points. This is an extensive data set which, one would hope, is less sensitive to statistical fluctuations than the more meager set from Boulder. Unfortunately, its interpretation is problematical.

From the clear-sky fit to the surface insolation data it is possible to obtain directly the clear-sky transmission function which we show in Figure 11 (filled circles). The results are extremely surprising as they indicate that the transmission in Cape Grim is almost constant with SZA, increasing slightly from 996/1365=0.73 at zenith to 208/(1365*0.2)=0.76 at 78°. Since TOA albedo is also increasing with SZA, this implies that absorption in a clear sky is *decreasing* as the sun approaches the horizon (from ~21% to ~8%); such a decrease in absorption is counter-intuitive since for larger SZA the pathlengths are longer. For comparison, similar data are shown in Figure 10 for Samoa along with the calculated clear-sky transmission (Figure 11, open circles); these latter data, which essentially mirror those from Boulder, show the expected decreasing transmission (from 0.74 to 0.45) over the same range of SZA.

To get some feel for the size of this anomaly, we note that if the transmission at Cape Grim followed that at either Samoa or Boulder the clear-sky surface insolation at 78° would be less by 85W/m^2 (the difference in transmissions multiplied by the TOA insolation, or (0.76-0.45)*273W/m^2=85W/m^2.

We do not understand the origin of this striking and unexpected behavior of the Cape Grim data but suggest that before the data set is adduced to argue a small (42W/m^2) inconsistency with CCM2 (see Figure 9) one should explain the large, unexpected trends.

iv) The Choice of Clear Sky Limit and its Effect on the Cloud Forcing Ratio

As a final exercise, we examine how the calculated value of the cloud forcing ratio, R, is affected by an arbitrary offset in the choice for clear-sky TOA flux and how R varies with cloud cover. The results are then compared with data from Samoa.

The equations relating R to clear and cloudy fluxes are:

$$R=\frac{Cs(S)}{Cs(TOA)}$$

$$R = \frac{(\overline{F_{so}} - \overline{F_{sc}})}{(\overline{F_{to}} - \overline{F_{tc}})} \qquad (2)$$

Here, $\overline{F_{to}}$ and $\overline{F_{tc}}$ are mean TOA fluxes for clear and cloudy skies, respectively, and $\overline{F_{so}}$ and $\overline{F_{sc}}$ are similarly the mean surface fluxes.

In order to usefully compare the CRF ratios found experimentally with the effects predicted by the model, the clear-sky fit as chosen from the data must be the same as that chosen from the output of the model. Let us assume that because of the uncertainty in determining a clear-sky fit, the mean clear-sky surface flux, $\overline{F_{so}}$, has been chosen slightly larger from the data than from the model's output. Referring to equation 2 above, it is clear that R will be larger than predicted by the model. Such a slight shift in the clear-sky determination has the most pronounced effect on the cloud forcing ratio for thin clouds; as cloud cover increases (large $\overline{F_{SC}}$) the fractional difference approaches the true value and, consequently, so does R. We would predict then that when the data are segregated according to cloudiness the cloud forcing ratio will be seen to decrease with cloud cover and approach the true value.

The data sets from Samoa and Cape Grim are large enough that binning according to cloud cover yields meaningful results. Both data sets show R to be dependent on the degree of cloud cover in a similar manner (private communication Prof. R. Cess). A changing R is contrary to equation 1 in which it has been assumed that β, and thus R, is independent of cloud cover. To bring the two into agreement we must either dispense with equation 1 or re-analyze the data in such a way as to obtain a constant R.

The data for Samoa, binned by cloud cover, are given in Figure 12a (as presented to us by Prof. Cess). As seen in the lower panel, when cloud cover (measured by TOA albedo) increases, the value of R calculated from the data decreases from 1.75 to 1.05, approaching the same forcing ratio predicted by the model. This data set, as pointed out by R. D. Cess et al. (1995), is particularly prone to a misidentification of the clear-sky limit due to the "broken cloud" effect; consequently, we attempted to shift the surface clear-sky flux by an amount that would produce a constant R.

Figure 12b includes both the forcing ratios in the lower panel of Figure 12a and our re-calculations of R after a shift of $45 W/m^2$ in the mean, clear-sky surface flux. The shifted data are seen to produce fairly constant values of R which are much closer to the value of R as calculated from the model.

The original choice of clear sky limits produces an average cloud forcing ratio of 1.5, similar to that obtained from the TOA albedo slope (Eq. 1). But, while the *average* R as obtained by the two methods agree, a changing R (from 1.75 to 1.05) is inconsistent with the basic assumptions used to derive Eq. 1. Our choice of clear-sky limit produces an almost constant R, in agreement with the premises of equation 1, but the value, 1.13, is no longer consistent with that obtained from the TOA albedo slope. Thus, either way, the two methods negate rather than support each other.

III. CONTRADICTORY ANALYSES OF THE BOULDER ERBE DATA

The same ERBE-derived data from Boulder which are used in R. D. Cess et al. (1995) have been analyzed previously with quite different results. In S. Nemesure et al. (1994) the authors used a plot of surface flux against TOA flux (Figure 13) to investigate the extent of cloud forcing. If a linear representation of this data is reasonable, the slope (0.84, R. D. Cess et al., 1993) is identical to the CRF ratio. A derivation relating the flux-flux regression to the CRF ratio is given in Appendix II.

Unfortunately, just as is the case with Figure 2, variation of the fluxes is due to both cloudiness and SZA, of which only the first allows a correct calculation of the CRF ratio. The authors were aware of this problem and so decided to separate the effects by fitting the surface flux in a double linear regression which contained both TOA flux and cos(SZA) as independent variables. The resulting coefficient of the TOA flux was then identified with the CRF ratio, this time with a value of 0.98 ± 0.05. They concluded that "the SW radiative cloud impact is neutral."

In the same paper a plot was made of % TOA albedo *vs.* surface insolation/cos (SZA). This type of plot is essentially the same as in Figure 2 and the resulting slope of -0.039 ± 0.004 can be related directly to β through the solar constant (for the months in which the data were taken), $\beta=(0.039)*1.36\times10^{3}/100=0.53$. Through Equation 1 and the average surface albedo of 0.18 (S. Nemesure et al., 1994) we can calculate a value of 1.55 ± 0.15 for the associated CRF ratio; this last analysis was the one presented in the 1995 paper.

The results of both analyses are presented in Figure 14. We see, first, that within this one data set, just due to different methods of analysis, the spread in results is larger than the effect attributed to enhanced solar absorption. Second, and more important, we see that the authors have seriously underestimated the uncertainties inherent in their methods of analysis. The problem is in considering only those uncertainties which are given formally by least-squares fits of the data to postulated functional relationships; such uncertainties tell us little about the adequacy of these presumed relationships. Finally, we see that while in the current paper the Boulder/ERBE data set has been adduced as a proof of the authors' hypothesis, a different analysis, previously published, gives contrary results. This disagreement goes unexplained.

FINAL WORDS

We have presented several reasons to question the content of this paper. It might be thought that by doing so we are attempting to disprove its main thesis, that cloudy skies absorb more short-wave radiation than predicted by ECMWF or CCM2. In fact, we realize that the models have many failings and we would not be at all surprised to find that they underestimate the atmospheric absorption of radiation - or that they overestimate it.

The most serious problem we have with this paper is not its stated hypothesis, but rather that without an exhaustive analysis of the possible errors, both in the data sets and the assumptions inherent in each analytical method, it is impossible to decide how much credence to place in any calculation of the cloud forcing. The duplication of the experiment at however many different sites can not serve to unmask systematic errors, nor can the simple multiplication of doubtful analytical methods lead to an acceptable solution.

FIGURE CAPTIONS

Figure 1. From R. D. Cess et al., Science, 1995.

Figure 2. From R. D. Cess et al., Science, 1995

Figure 3. Plots of TOA albedo *vs* transmission illustrating the large scatter in the data, **a)** for Boulder, same as Figure 2, with clear-sky points removed (provided by R. Cess) and **b)** the three year cloudy data ($T<0.63$) from Samoa (provided by R. Cess from lecture slides). Both include three fits, linear, exponential and quadratic, all with very low correlation co-efficients due to the large scatter.

Figure 4. TOA albedo *vs* transmission for data binned by transmission. Binning for the Cape Grim and Samoa data was done by R. Cess while we binned those from Boulder. **a)** linear and **b)** quadratic fits.

Figure 5. The slopes from Figures 4a and 4b.

Figure 6. **a)** TOA net flux *vs* cos(SZA) Boulder ERBE clear-sky data (from R. D. Cess et al. 1993) with a linear fit.
b) The residuals from the linear fit, suggesting that clear-sky is not well defined on a scale of $45W/m^2$.

Figure 7. **a)** Surface net flux *vs* cos(SZA) with a linear fit. Boulder ERBE clear-sky data (from R. D. Cess et al. 1991).
b) The residuals from the linear fit.

Figure 8. Boulder surface insolation all-sky data (from R. D. Cess et al. 1993). Two methods for determining clear-sky limit are compared. The lower line is based on ERBE scene ID as reported by R. D. Cess et al. (1993). The second, clear-sky fit is based on the upper-envelope method (binning by cos(SZA) = 0.05). There is a difference of $30W/m^2$ between the two methods. Because of the small number of points, the upper envelope, clear-sky fit is very sensitive to the width of the bins; the finer the bin, the lower the clear-sky limit.

Figure 9. The Cape Grim all-sky TOA flux and surface insolation *vs* cos(SZA) with clear-sky fits (provided by R. Cess).

Figure 10. The Samoa all-sky TOA flux and surface insolation *vs* cos(SZA) with clear-sky fits (provided by R. Cess).

Figure 11. Clear-sky transmission as a function of cos(SZA) for Samoa and Cape Grim, based on Figures 9 and 10, assuming a TOA insolation at zenith of $1365W/m^2$. Note that for Cape Grim the clear-sky transmission increases as the Sun approaches the horizon.

Figure 12. The dependence of CRF ratios on cloud cover in Samoa. Figure 12a consists of data from a lecture slide from Prof. R.D. Cess. The upper panel gives the frequency of various cloud thicknesses. The middle panel shows the cloud-radiative-forcing, for TOA (open bars) and surface (filled bars). The lower panel gives the CRF ratio. In Figure 12b, the hatched bars represent the same CRF ratios as in the lower panel of Figure 12a; the gray bars are CCM2 predictions. Note that the CRF ratios approach the model predictions as cloud cover increases. Also included (open bars) are ratios calculated by shifting the surface clear-sky limit by $45 W/m^2$. This simple shift brings the model and data into reasonable agreement.

Figure 13. Boulder ERBE data as taken from R. D. Cess et al. 1993. Two of the three straight lines represent fits of TOA flux to surface flux and *vice versa*. The third is drawn with a slope appropriate to the β value reported (S. Nemesure et al. 1994 and R. D. Cess et al. 1995).

Figure 14. The black circle denotes the CRF ratio from S. Nemesure et al. 1994, obtained by a two variable regression of surface flux to TOA flux and cos(SZA). Gray circles are from S. Nemesure et al. 1994 and R. D. Cess et al. 1995, as determined by the TOA albedo slope and Equation 1 (using 0.18 for surface albedo). Error bars are either those given in the 1994 and 1995 papers or calculated from them using Equation 1. Note that the error bars (95% confidence) are much smaller than the spread in the results. The current, 1995, paper repeats one of the results given in S. Nemesure et al. 1994. The squares represent model predictions from R. D. Cess et al. 1995.

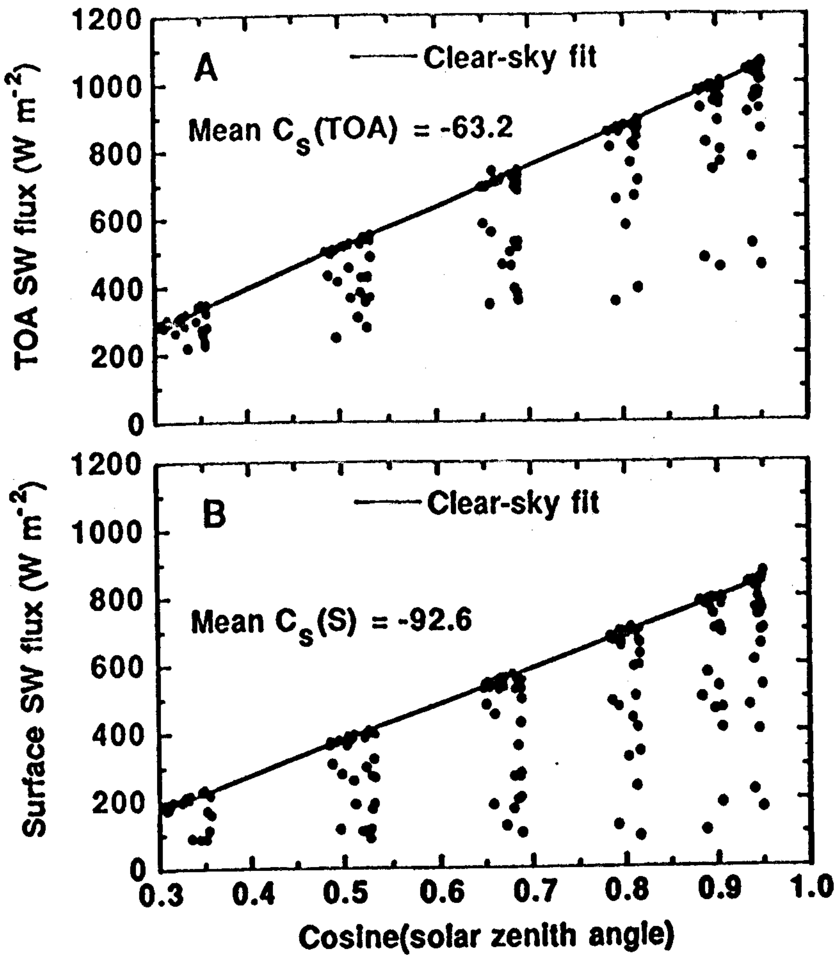


Fig. 1. (A) The net downward SW flux at the TOA, as measured by GOES at the BAO tower, as a function of the cosine of the solar zenith angle. (B) The same as (A) but for the tower-measured net downward SW flux at the surface.

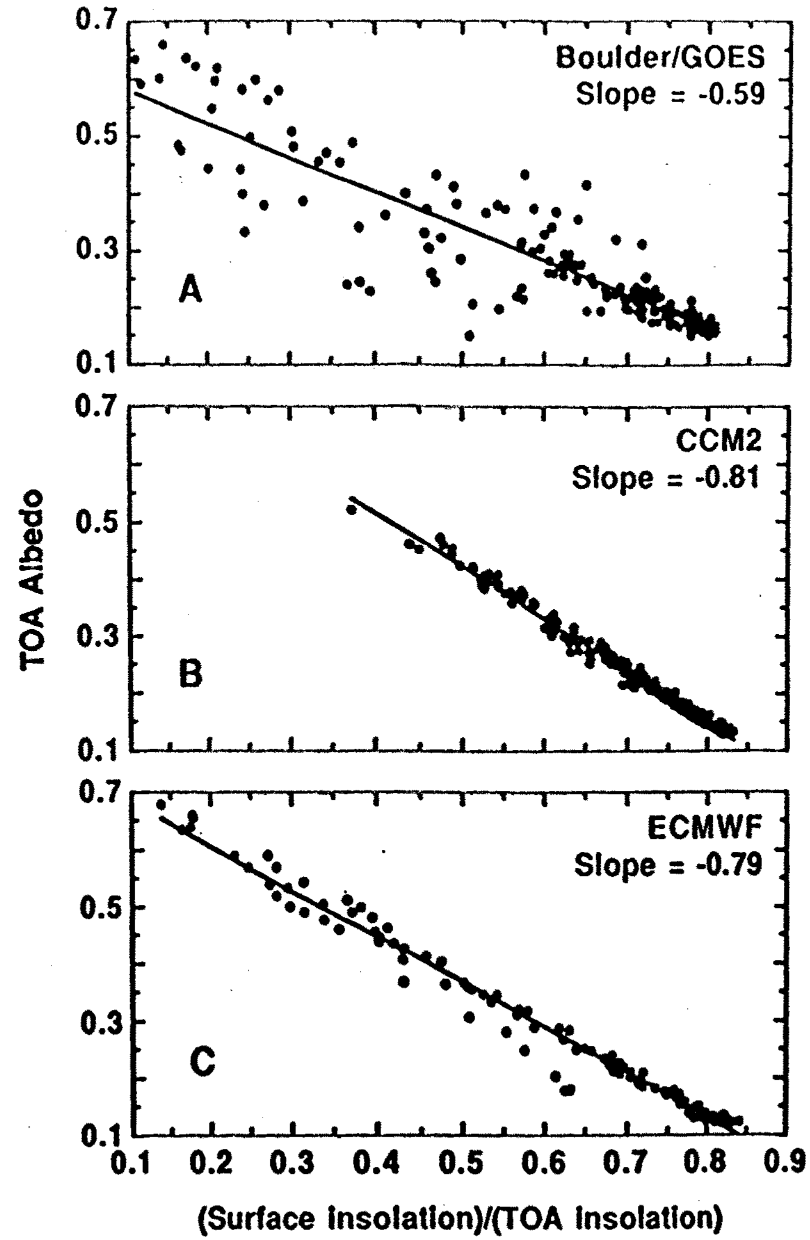
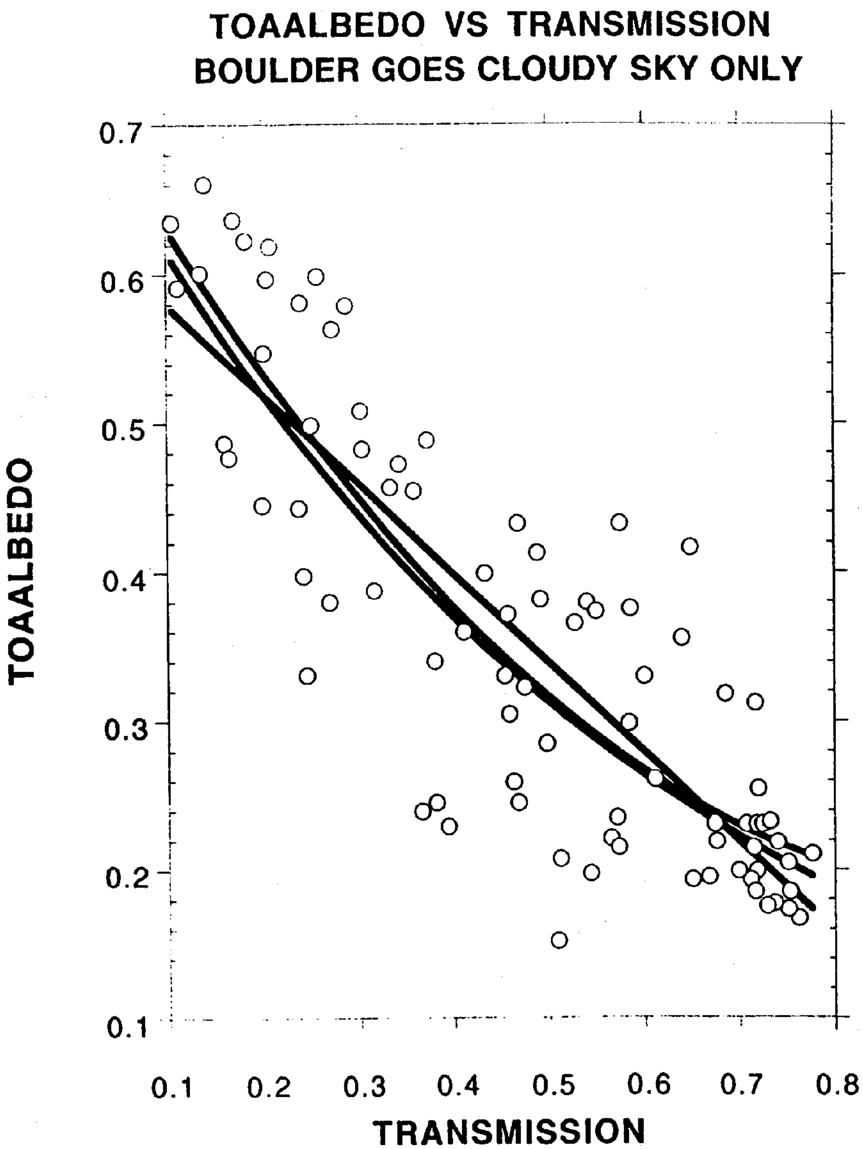


Fig. 2. (A) Scatter plot of the GOES TOA albedo as a function of surface insolation (measured at the BAO tower) divided by the TOA insolation. (B) The same as (A) but for CCM2. (C) The same as (A) but for the ECMWF GCM.

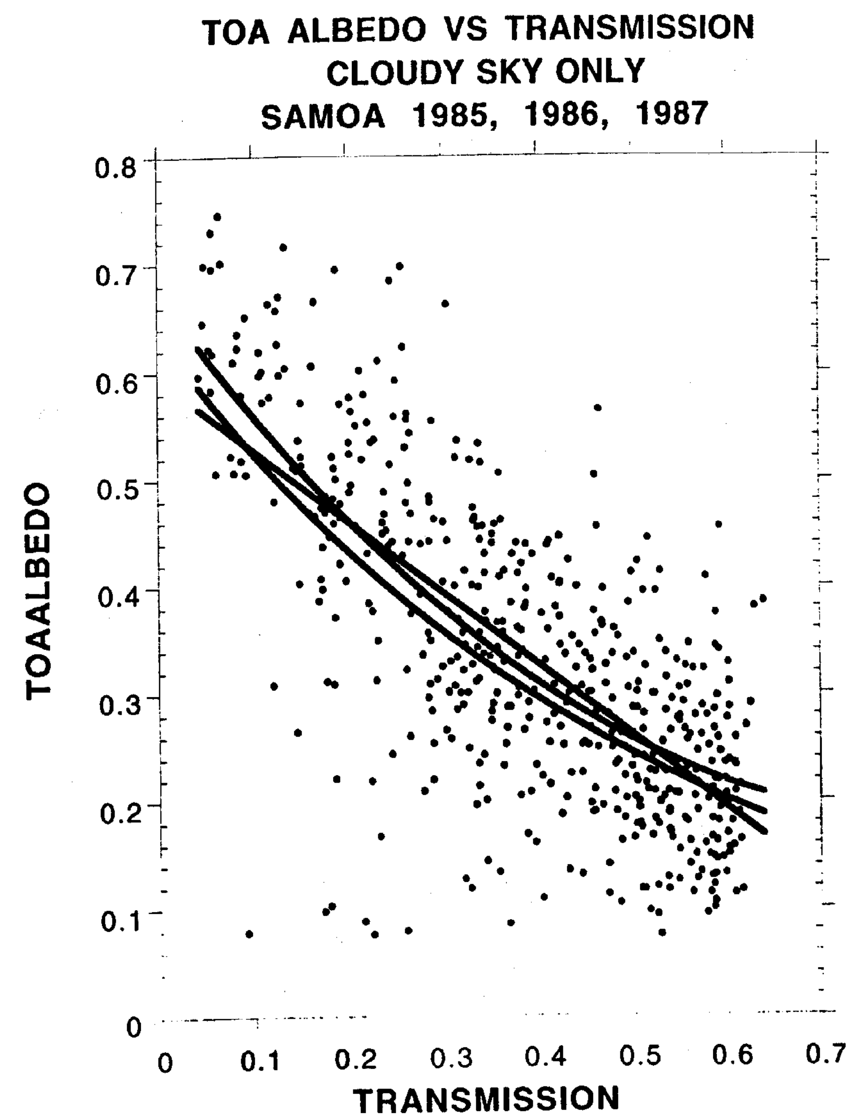


$\alpha_t = 0.64 - 0.60*T$ R=0.84

$\alpha_t = 0.74 - 1.14*T + 0.59*T^2$ R=0.84

$\alpha_t = 0.73*e^{(-1.69*T)}$ R=0.855

Figure 3a



$\alpha_t = 0.60 - 0.67*T$ R=0.70

$\alpha_t = 0.67 - 1.2*T + 0.74*T^2$ R=0.71

$\alpha_t = 0.64*e^{(-1.9*T)}$ R=0.71

Figure 3b

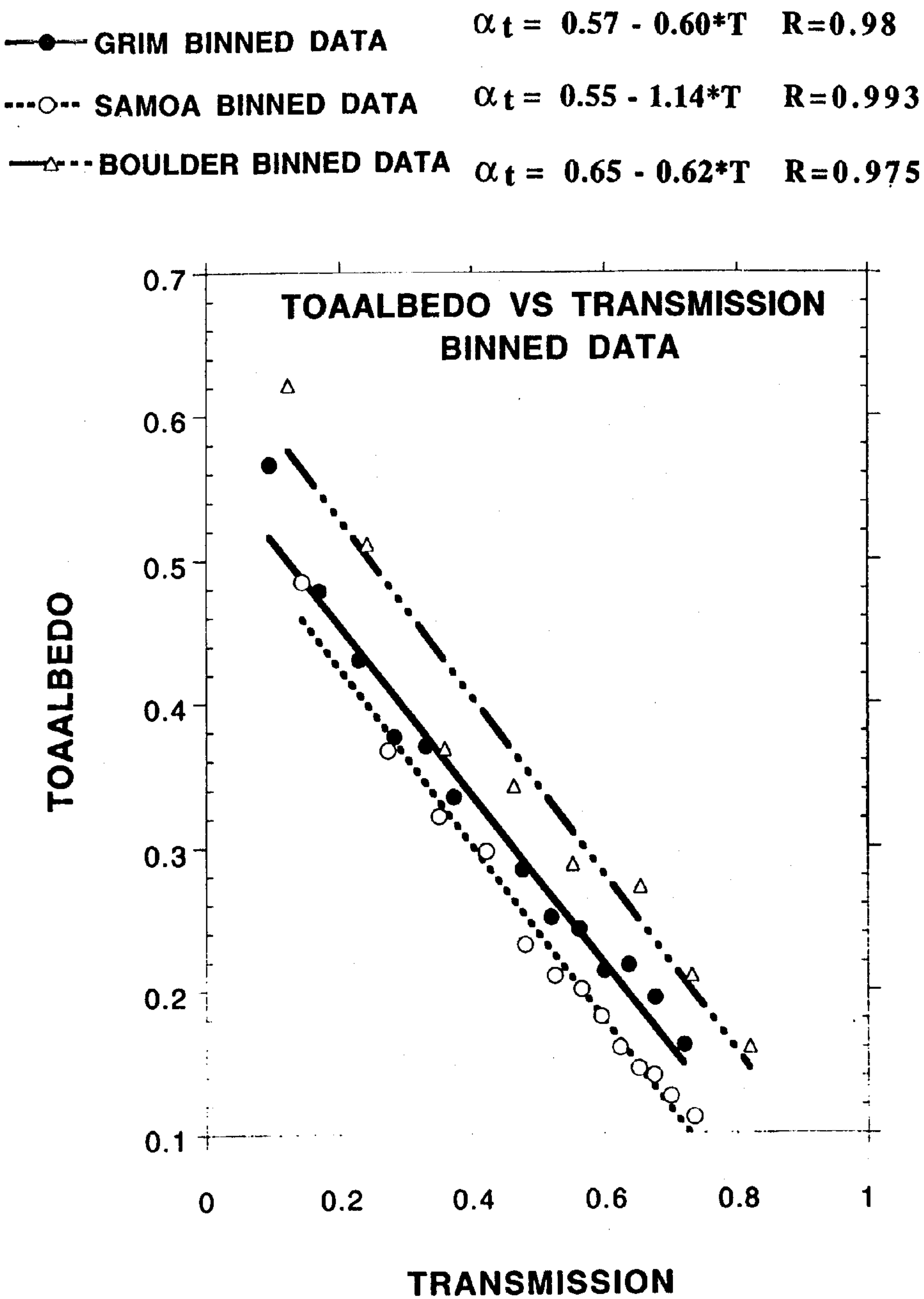


Figure 4a

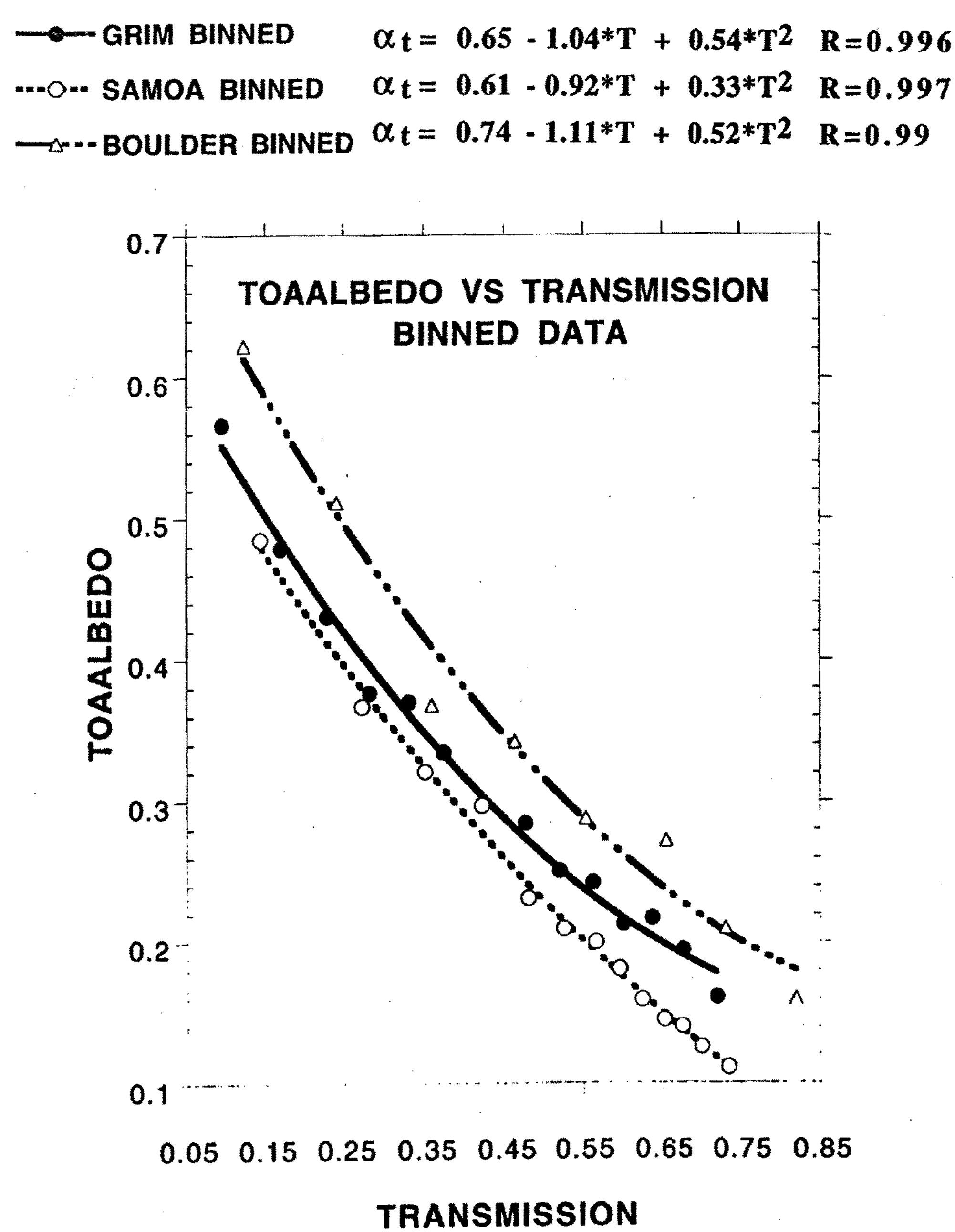


Figure 4b

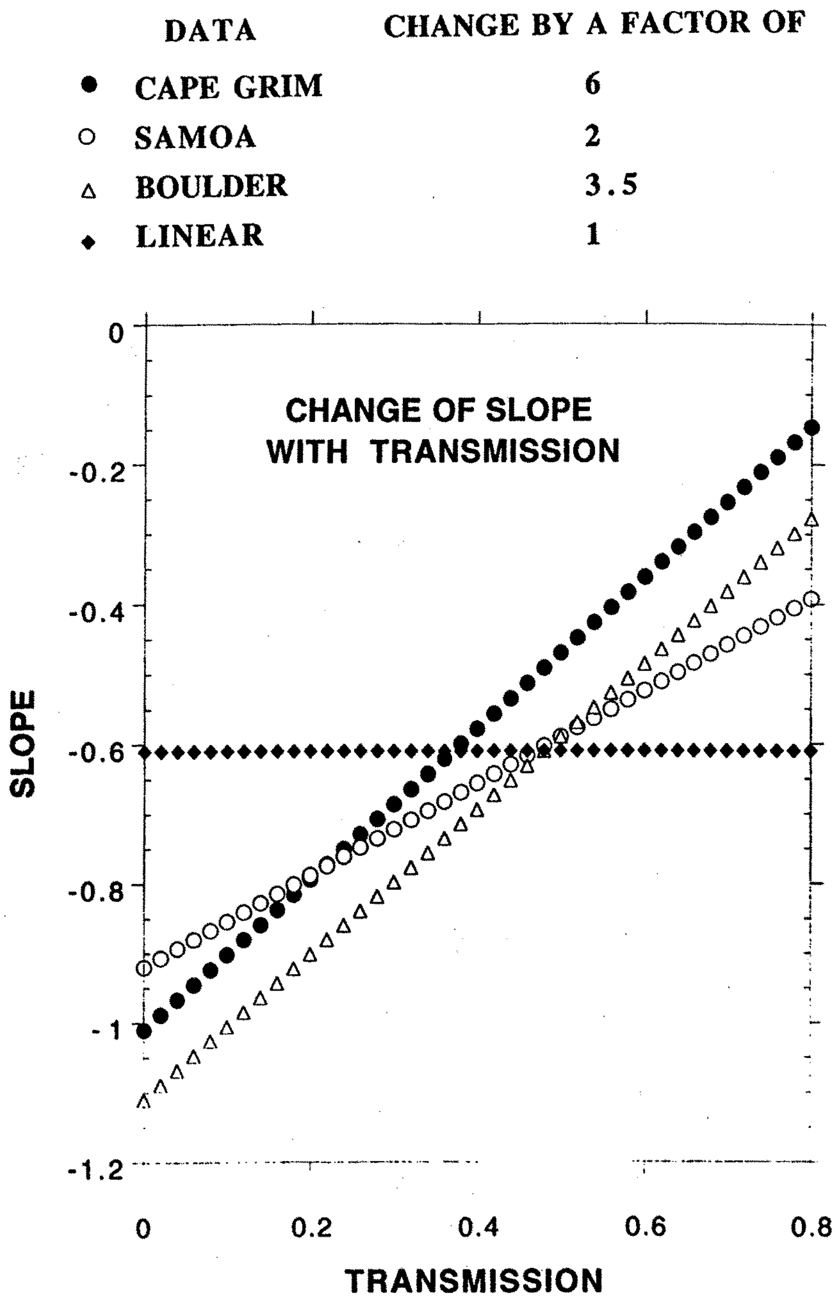


Figure 5

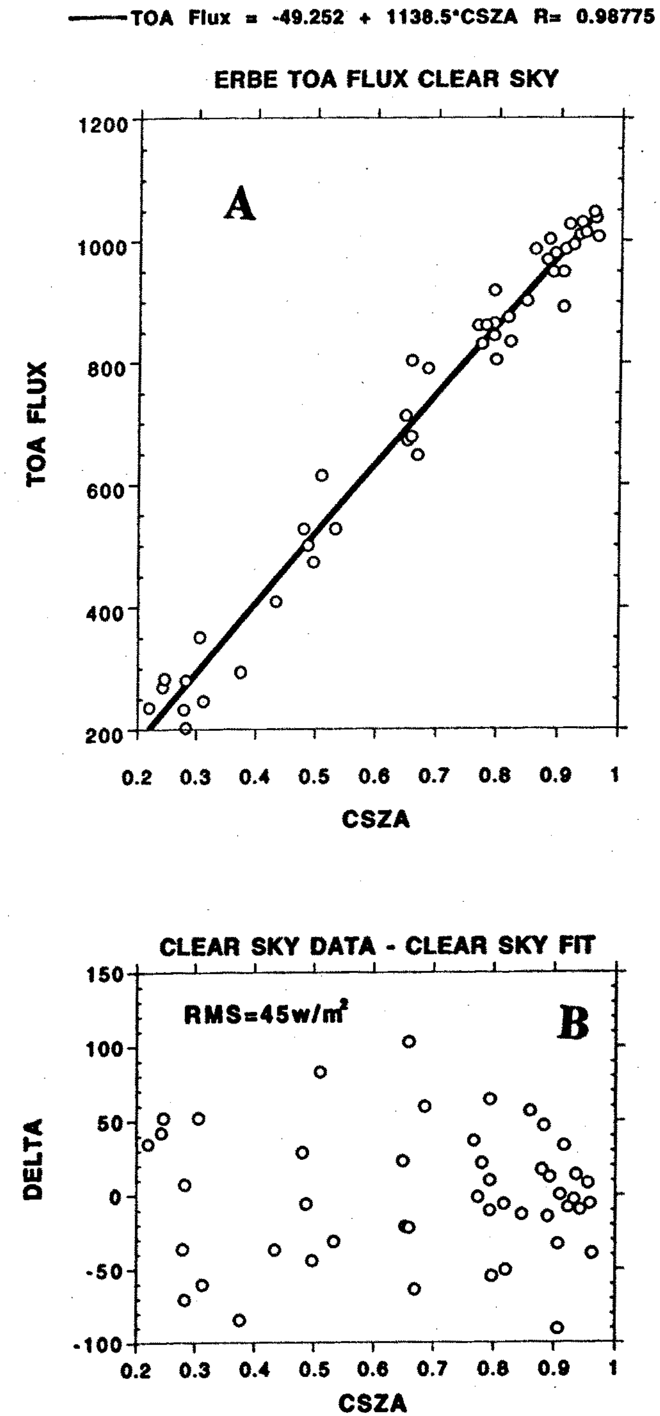


Figure 6

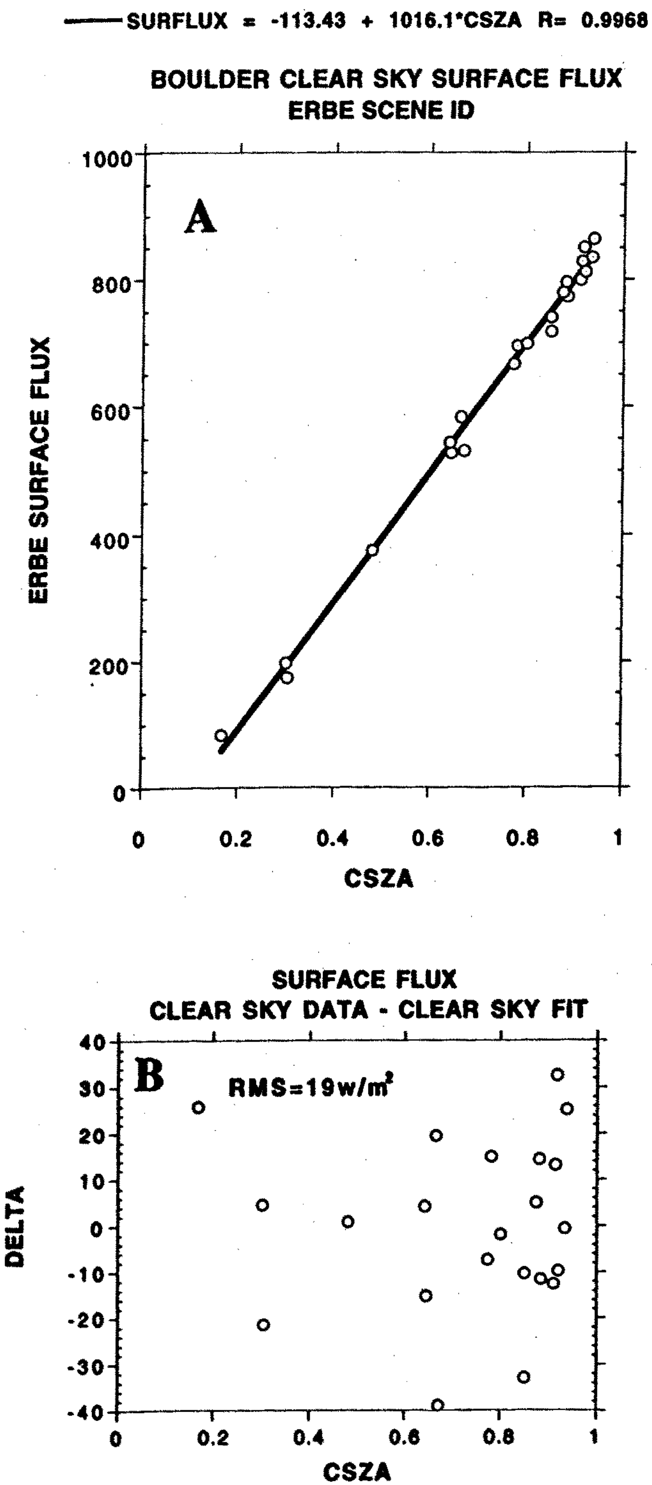


Figure 7

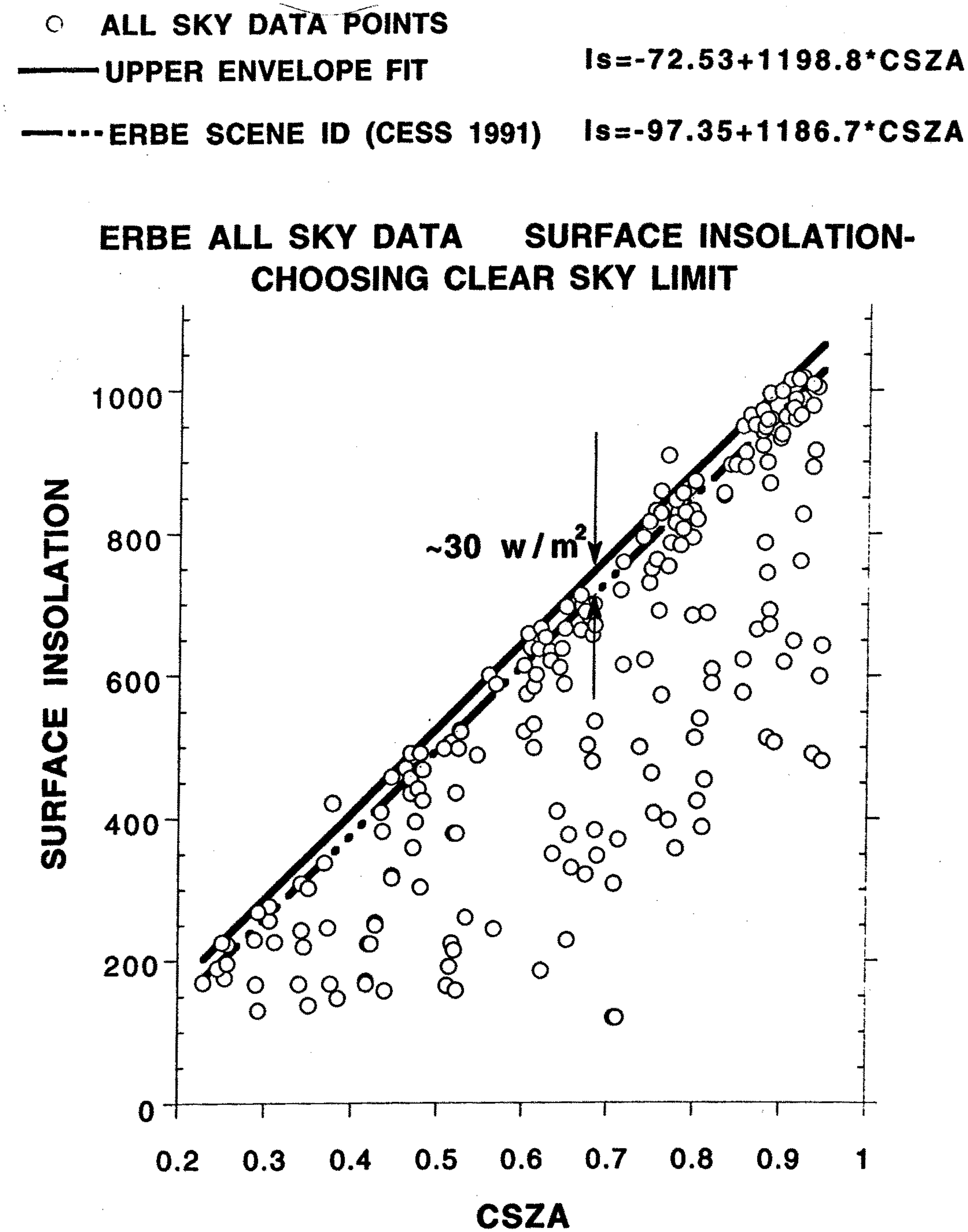
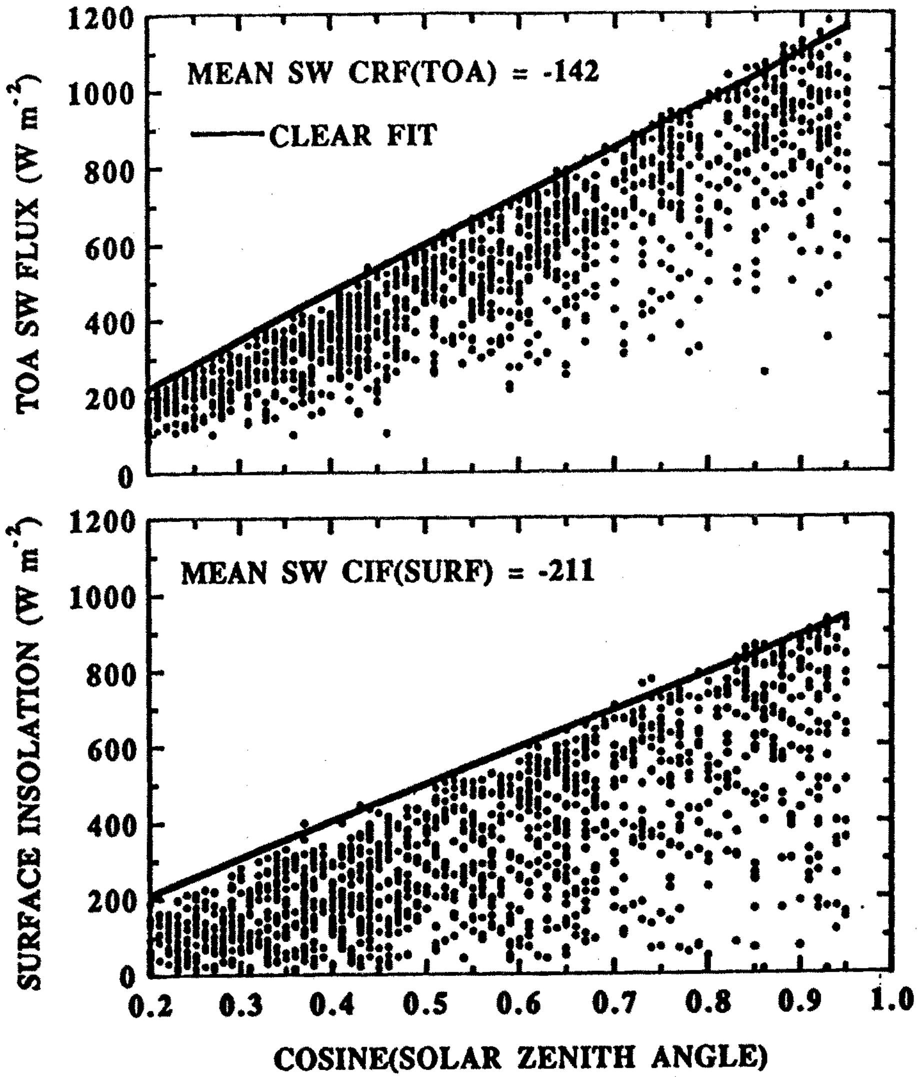


Figure 8



CCM2

MEAN CRF(TOA) = -140
MEAN CIF(SURF) = -167

Figure 9

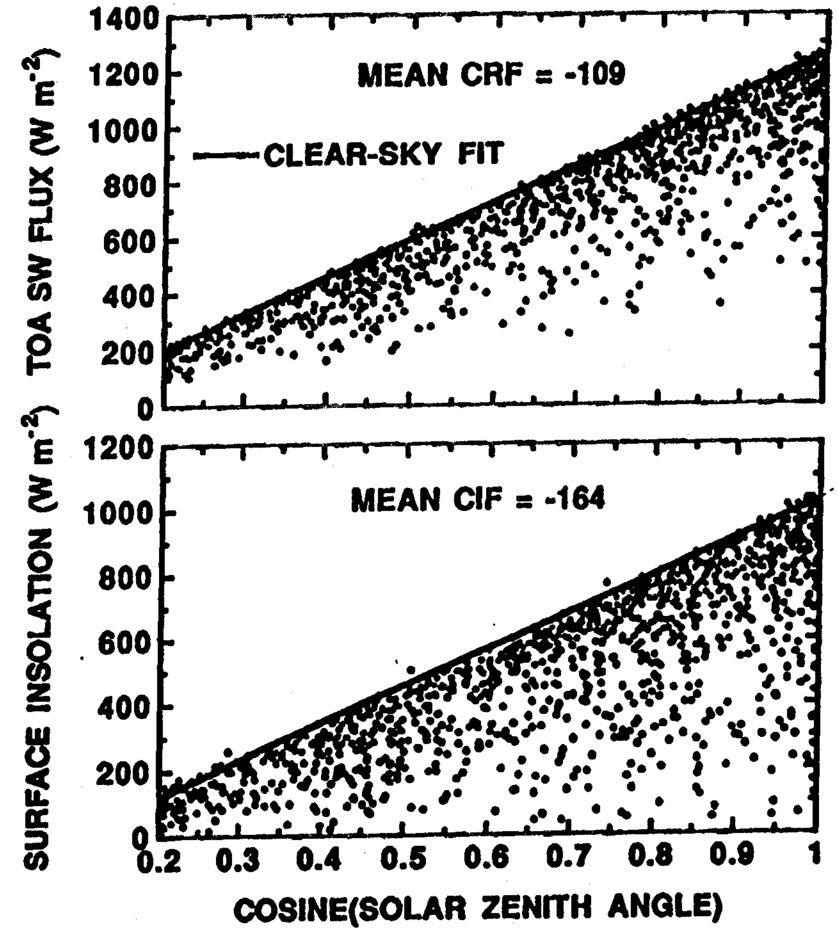


Figure 10

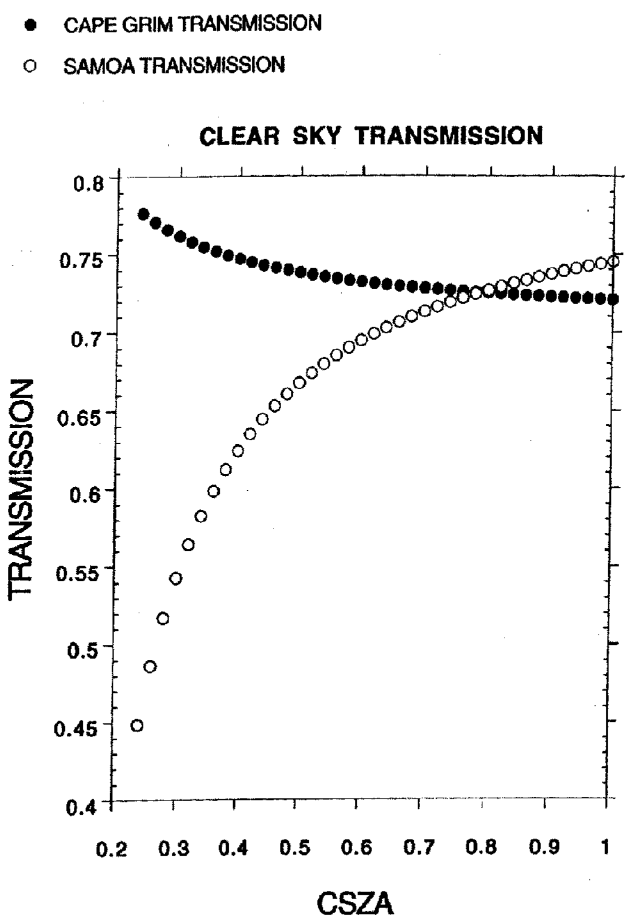


Figure 11

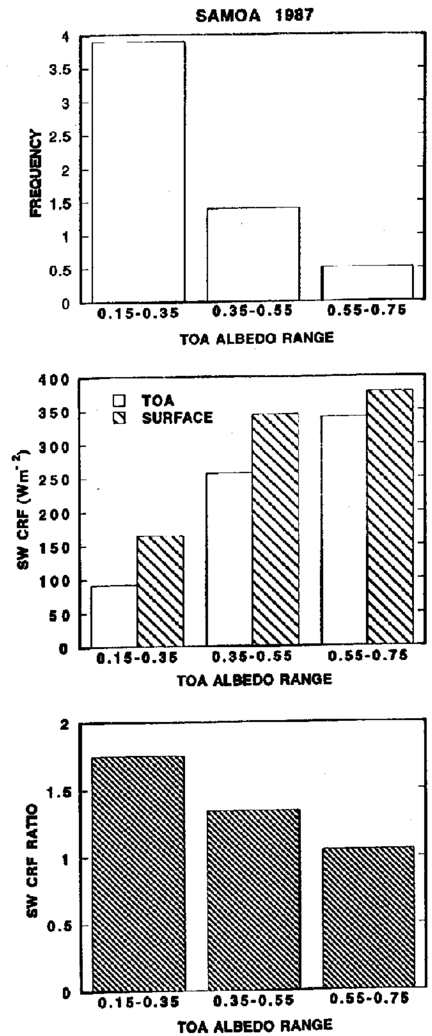


Figure 12a

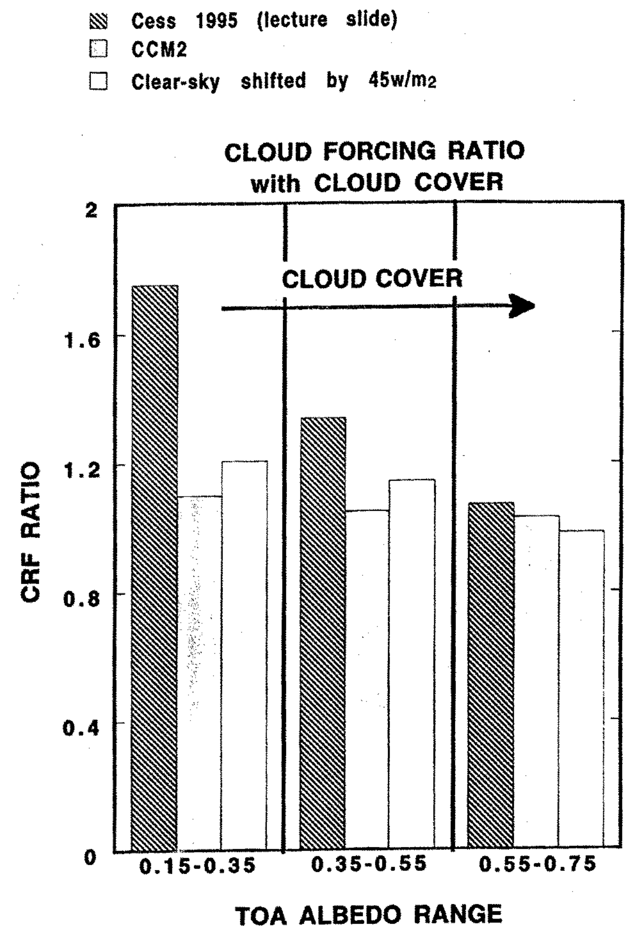
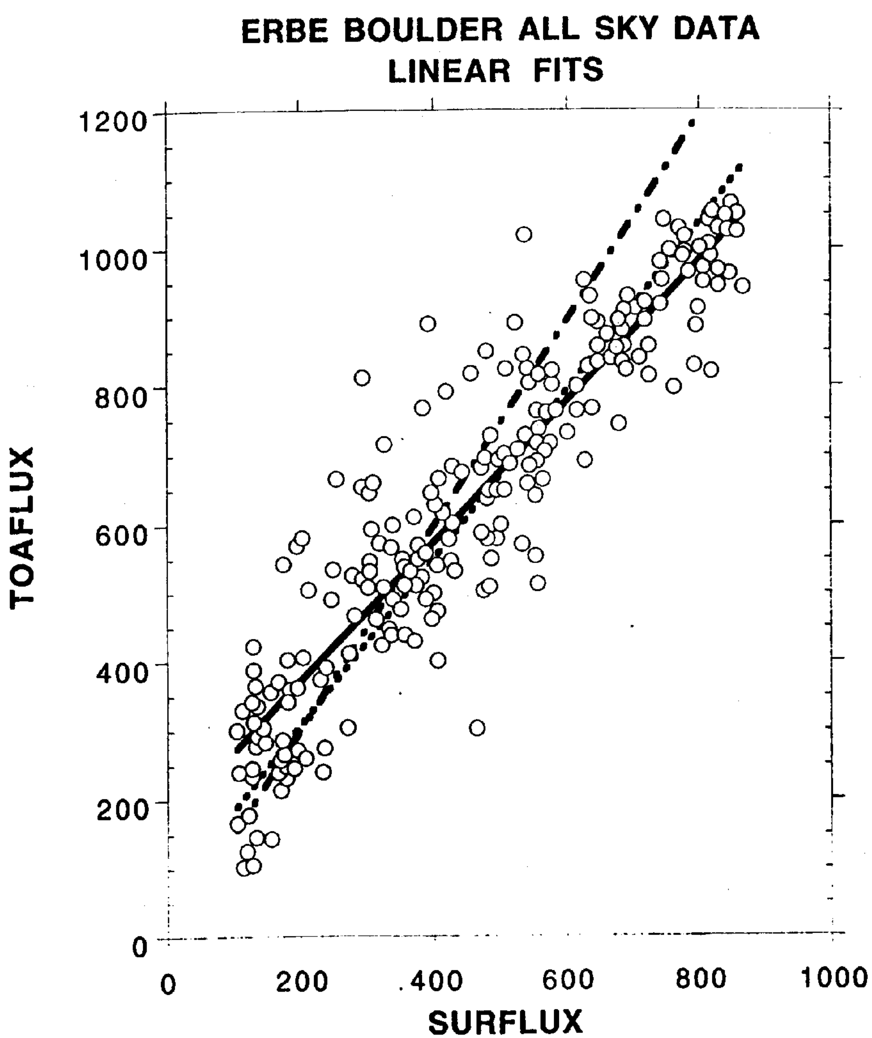


Figure 12b



——— TOAFLUX = 166 + 1.02*SURFLUX R=0.914
······· SURFLUX = -61 + 0.82*TOAFLUX R=0.914
–·–· TOAFLUX = 1.55*SURFLUX

Figure 13

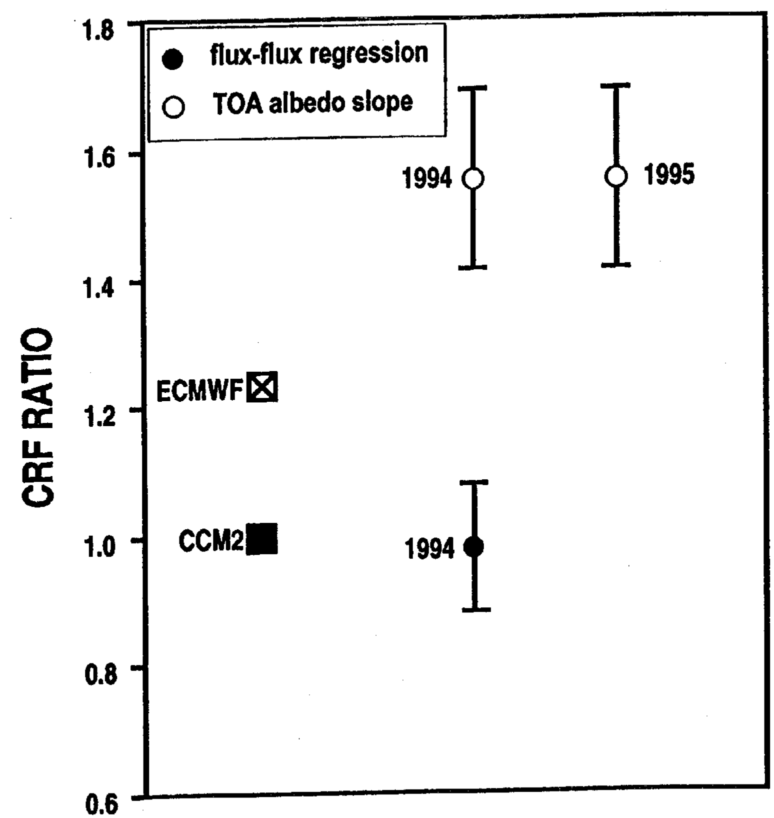


Figure 14

APPENDIX I

Derivation of Equation 1

I_t = TOA insolation
I_s = surface insolation
R_t = Reflected back to space
T = Transmission
F = Net flux
α_s = surface albedo(in general a function of SZA and of cloud cover)
α_t = TOA albedo
β = -(slope of the TOA albedo to transmission plot)
μ = cos(SZA)
X_o means X for clear sky
X_c means X for cloudy (all) sky
$\overline{X}$ means average in the normal sense (mean)
{ } means average in the radiation community sense defined as:

$$\{\alpha_t\} = \frac{\overline{R_t}}{\overline{I_t}}$$

$$\{\alpha_s\} = 1 - \frac{\overline{F_s}}{\overline{I_s}}$$

$$\{T\} = \frac{\overline{I_s}}{\overline{I_t}}$$

define CRFt= $I_{tc}\,\alpha_{tc} - I_{to}\,\alpha_{to}$ the instantaneous cloud reflective forcing at TOA referenced to a clear sky

define Cs(TOA) = $\overline{CRFt} = \overline{I_{tc}\,\alpha_{tc}} - \overline{I_{to}\,\alpha_{to}}$ this average is over all cloudy conditions and all SZA

then Cs(TOA) = $\overline{I_{tc}}\,\{\alpha_{tc}\} - \overline{I_{to}}\,\{\alpha_{to}\}$

define CRFs $= (1-\alpha_{sc})I_{sc} - (1-\alpha_{so})I_{so}$ the instantaneous cloud forcing at the surface

$$\text{define } Cs(S) = \overline{CRFs} = \overline{(1-\alpha_{sc})I_{sc}} - \overline{(1-\alpha_{so})I_{so}}$$

$$\text{then } Cs(S) = (1-\{\alpha_{sc}\})\,\overline{I_{sc}} - (1-\{\alpha_{so}\})\,\overline{I_{so}}$$

then,

$$\frac{Cs(S)}{Cs(TOA)} = \frac{(1-\{\alpha_{sc}\})\,\overline{I_{sc}} - (1-\{\alpha_{so}\})\,\overline{I_{so}}}{\overline{I_{tc}}\,\{\alpha_{tc}\} - \overline{I_{to}}\,\{\alpha_{to}\}} \qquad \text{A 1}$$

To proceed with the derivation we need to make two approximations.

I. $\{\alpha_{sc}\} = \{\alpha_{so}\} = \{\alpha_s\}$ that is, the average surface albedo is the same for cloudy and clear skies. Although Prof. Cess states (private communication) that this is true for the Boulder data, we know that surface albedo is a function of cloud cover and, even if for Boulder the cloudy and clear skies give the same average, it is not known if this approximation is generally applicable.

II. $\overline{I_{tc}} = \overline{I_{to}} = \overline{I_t}$

To satisfy this equality requires that for every SZA sampled the ratio of the number of clear-sky to cloudy-sky points be the same. This is reasonably accomplished in the paper by fitting the clear-sky fluxes to straight lines and then using the fits to generate a surrogate data-set

Plugging approximations I and II into **A1** we get

$$\frac{Cs(S)}{Cs(TOA)} = \frac{[\overline{Isc} - \overline{Iso}](1-\{\alpha s\})}{\overline{It}\ [\{\alpha tc\} - \{\alpha to\}]} \qquad \text{A 2}$$

Now we must relate the above ratio to the slope in figure two, where TOA albedo is plotted against transmission.

To do this we must make a third assumption, that α_t is linearly related to T

then $$\alpha_t = C_1 - C_2T$$

from above $$\alpha_t = \frac{R_t}{I_t} \text{ and } T = \frac{I_s}{I_t}$$

then $$\frac{R_t}{I_t} = C_1 - \frac{C_2 I_s}{I_t}$$

$$R_t = C_1 I_t - C_2 I_s$$

Now we assume that all clear-sky points are on the same line as the cloudy-sky points, **defined by the same C_1 and C_2 as for cloudy sky.**

then for an arbitrary clear sky point with reflected light R_{to}, surface insolation Iso and TOA insolation Ito

$$R_{to} = C_1 I_{to} - C_2 I_{so}$$

Now, averaging <u>both</u> sides, remembering the difference between {X} and $\overline{X}$ and assuming again that $\overline{I_{to}} = \overline{I_t}$,

$$\overline{R_{to}} = C_1 \overline{I_t} - C_2 \overline{I_{so}}$$

$$\frac{\overline{R_{to}}}{\overline{I_t}} = C_1 - C_2 \frac{\overline{I_{so}}}{\overline{I_t}}$$

$$\{\alpha_{to}\} = C_1 - C_2 \frac{\overline{I_{so}}}{\overline{I_t}}$$

Similarly for cloudy sky

$$\{\alpha_{tc}\} = C_1 - C_2 \frac{\overline{I_{sc}}}{\overline{I_t}}$$

then, using the last two equations to solve for C_2,

$$C_2 = - \frac{\overline{I_t}\ [\{\alpha_{tc}\} - \{\alpha_{to}\}]}{[\overline{I_{sc}} - \overline{I_{so}}]}$$

or, using **A2**,

$$\frac{Cs(S)}{Cs(TOA)} = \frac{(1-\{\alpha_s\})}{-C_2} \qquad \textbf{A 3}$$

which is equation 1 in the paper, with $\beta = -C_2$

By making the above assumptions we imply, first, that the cloud forcing ratio can be determined by C_2 and, second, that this is the same C_2 as defined by the clear-sky data. The necessary conclusion is that any difference in cloud forcing ratio between the models and reality is due entirely to the models' treatment of clear sky.

APPENDIX II

CRF Ratio From the Flux-Flux Slope

From Cess 1994 assuming that surface flux is related to TOA flux by:

$F_s = D_o + D_1 F_t + D_2 \mu$ then

$F_{so} = D_o + D_1 F_{to} + D_2 \mu$ for clear sky

$F_{sc} = D_o + D_1 F_{tc} + D_2 \mu$ for cloudy sky

and for constant μ

$\Delta F_s = D_1 \Delta F_t$

with Δ the difference between clear and cloudy-sky

$\overline{\Delta F_s} = D_1 \overline{\Delta F_t}$

$Cs(S) = D_1 Cs(TOA)$

$$\frac{Cs(S)}{Cs(TOA)} = D_1 = \text{THE CRF RATIO}$$