tion [figure 1 in (*5*)]. These results suggest that there are problems (*7*) with the indirect slope method used by Cess *et al.* (*3*). For example, the slope results in figure 6 in the report by Pilewskie and Valero (*5*) predicts that a cloud of 45% albedo absorbs in excess of 40% of the incident solar radiation, a result unsupported in their figure 1.

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2. G. L. Stephens and S.-C. Tsay, *Q. J. R. Meteorol. Soc.* **116**, 671 (1990).
3. R. Cess *et al.*, *Science* **267**, 496 (1995).
4. G. L. Stephens, *J. Atmos. Sci.* **35**, 2111 (1978); S. Twomey, *ibid.* **33**, 1087 (1976); R. Davies *et al.*, *ibid.* **41**, 2126 (1984).
5. P. Pilewskie and F. Valero, *Science* **267**, 1626 (1995).
6. One can convert the flux difference measurements in the report by Pilewskie and Valero [figure 3 of (*5*)] to a fractional flux difference, which they would interpret as the fractional absorption. The mean values of the "absorption" would then range from approximately from 10% to 14%, which is entirely in keeping with theory. For reasons noted below (*8*), more significance should be attached to average values than to individual values [given in figure 2 of (*5*)].
7. This conclusion prompted other investigators to devise different ways of measuring absorption. An example is that of M. King *et al.* [*J. Atmos. Sci.* **47**, (1990)] who show slight discrepancies between theory and observation, but which is of a nature discussed by Stephens and Tsay (*2*) and does not support the results of Cess *et al.* (*3*).
8. T. Hayasaka *et al.*, *J. Appl. Meterol.* **34**, 1047 (1995). It is a typical practice to average the data in a effort to remove these spurious effects. Correction methods have also been developed, for example, by S. A. Ackerman and S. K. Cox [*ibid.* **20**, 1510 (1981)], to account for the spurious effects of undersampling solar fluxes around clouds. Correction methods were not used by Pilewskie and Valero (*5*).
9. A significant problem of the analyses by Cess *et al.* (*3*) is the assertion that reflection is a function of transmission. At absorbing wavelengths this assumption is wrong. The scattering and absorbing processes responsible for the measured albedo occur largely in the upper part of the cloud. Transmission depends on how these processes take place and not the other way around. It is more appropriate, at least on physical grounds, to consider transmission as a function of reflection (although even this is also not entirely correct). If the data of figure 6 of (*5*) are refitted with the dependent variables flipped, a slope of −0.82 results (which agrees with theory to the extent that the slope method is sensible). We use the model of Q. Fu and K. N. Lioa [*J. Atmos. Sci.* **50**, 2008 (1993)].
10. Theory predicts little solar absorption in the visible portion of the spectrum. Cess *et al.* imply that absorption of visible light by aerosol is unlikely to be the culprit, as they find similar anomalous values of β from flux data obtained in clean air masses over Cape Grim, Tasmania, Australia, where the relative cleanness of the air and its chemistry is well documented.
11. T. Nakajima *et al.*, *J. Atmos. Sci.* **48**, 728 (1991). There is a slight discrepancy between retrieved particle size and measured particle size. The retrieved particle sizes are typically a few microns larger than measured and explanation of the discrepancy has been elusive. It is, however, not close to the difference implied by the results of Cess *et al.* (*3*).
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14. W. L. Smith Jr. *et al.*, *Mon. Weather Rev.* **118**, 2389 (1990).

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Response: Stephens reflects a traditional viewpoint in stating that cloud "absorption occurs in place of rather than in addition to clear sky absorption." This is why theoretical cloud radiative transfer models predict roughly the same clear-sky and cloudy-sky (all-sky) solar absorption. But independent studies by Ramanathan *et al.* (*1*), Cess *et al.* (*2*), and Pilewskie and Valero (*3*) indicate that real clouds (or clouds plus atmosphere) absorb more solar radiation than do models. Stephens interprets the data in the report by Cess *et al.* (*2*) with the use of an atmospheric radiation model that adopts conventional plane-parallel clouds. He implements into this model a wavelength-dependent enhanced cloud absorption without adequate explanation; there are an infinite number of ways this calculation could be done, with probably infinite possible conclusions.

Stephens states that a "significant problem of the analysis by Cess *et al.* is the assertion that reflection is a function of transmission," which refers to the albedo versus transmittance regression. But as was demonstrated (*2*) for the Boulder-GOES data (obtained from the Geostationary Operational Environmental Satellite), the regression analysis was consistent with a direct determination of shortwave (SW) cloud-radiative forcing at the surface, $C_s(S)$, and at the top of the atmosphere, $C_s(TOA)$. This produced $C_s(S)/C_s(TOA) = 1.46$, a value that is in agreement with 1.41 from the regression analysis. Similar $C_s(S)/C_s(TOA)$ values were obtained in the other studies (*1–3*). In contrast, theoretical models produce $C_s(S)/C_s(TOA) \approx 1$, and this difference can only be explained by the models underestimating cloudy-sky absorption relative to clear-sky absorption (*1–3*).

Cess *et al.* (*2*) adopted the regression analysis for two reasons. First, only surface insolation was available at the other sites so it was not possible to directly determine $C_s(S)$. Second, the regression analysis did not require clear-sky identification of the surface measurements, which was difficult to determine for some data. But it is a simple task to demonstrate [in a manner analogous to what was done for the Boulder-GOES data, and using data for which we can confidently identify clear surface measurements (*4*)] that the regression analysis is consistent with an alternate treatment of TOA and surface measurements. With α denoting the TOA albedo and T the atmospheric transmittance (surface insolation divided by TOA insolation), it is straightforward to show that

$$\Delta\alpha/\Delta T = -(N-N_c)/(I-I_c) \qquad (1)$$

where N is the net downward SW radiation at the TOA, I is the surface insolation, and N_c and I_c refer to clear-sky conditions. One can compare $\Delta\alpha/\Delta T$ (Fig. 1) as evaluated from regressions to that determined from Eq. (1), which addresses the issue of temporal and spatial sampling errors raised by Stephens. Equation 1 requires only that such errors be random so that they average to zero when evaluating the numerator and denominator of Eq. 1. The α versus T regression, however, explicitly requires all errors to be in the satellite measurements; if they were in the surface measurements, then a T versus α regression would be required, and $\Delta\alpha/\Delta T$ would be increased by the factor $1/R^2$, where R is the correlation coefficient. Sampling errors are attributable to the satellite measurements as demonstrated by the agreement between Eq. 1 and $\Delta\alpha/\Delta T$ as evaluated from the α versus T regression (Fig. 1). If it were more appropriate, as Stephens suggests, to consider T as a function of α, then Eq. 1 should agree with $\Delta\alpha/\Delta T$ as determined from the T versus α regression. This is not the case (Fig. 1), except for Oklahoma, where the large R makes the choice of the regression immaterial.

The reason that sampling errors are not attributable to the surface measurements is partially a result of temporal averaging of the surface measurements. Sampling errors occur because the satellite pixel measurements are instantaneous and over a grid that is much larger than the field of view of an upward facing pyranometer. For example, a single isolated cloud could significantly impact the surface measurement while having little impact on the satellite measurement; the reverse would occur if there were clouds over most of the satellite grid, but not over the surface instrument. But cloud systems move, so that temporally averaging the surface measurements is equivalent to spatially averaging them over the satellite grid. The Oklahoma data demonstrate this point: The regression R

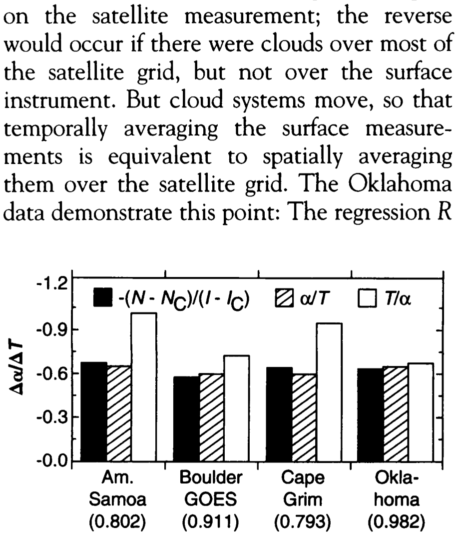

Fig. 1. $\Delta\alpha/\Delta T$ determined from Eq. 1, from an α versus T regression, and from a T versus α regression, for four geographically diverse locations. Correlation coefficients are indicated at bottom.

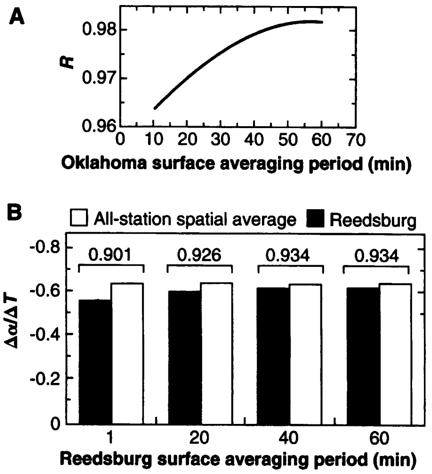

Fig. 2. (**A**) α versus T correlation coefficients (Oklahoma) as a function of the surface averaging period, which constitutes an average of the near-instantaneous surface measurements temporally centered about the time of the instantaneous satellite measurements. (**B**) $\Delta\alpha/\Delta T$ for a single station (Reedsburg) of the Wisconsin pyranometer network as a function of the surface averaging period at that site and as determined by spatially averaging the entire 11 stations within the network. All-station spatial averages adopt 1-minute surface averages and are invariant to the Reedsburg averaging period. The Reedsburg correlation coefficients are shown, and $R = 0.962$ for the all-station spatial average.

is a maximum for a surface averaging period of roughly 60 minutes (Fig. 2A), which is the averaging period used for that data. The Wisconsin data (*2*) directly demonstrate equivalence between temporal and spatial averaging. The surface measurements are from a network of 11 pyranometers located within a roughly 0.8° × 0.8° grid. The data are available as 1-minute means, and when spatially averaged over all stations the resulting $\Delta\alpha/\Delta T$ is comparable to that for a single station (Reedsburg) when the single-station measurement has been temporally averaged (Fig. 2B). For the other sites the surface measurements were available as 1-hour (American Samoa and Boulder) or half-hour (Cape Grim) means, and these temporal averages should minimize spatial sampling errors associated with the surface measurements as is consistent with Fig. 1A.

The issue raised by Stephens concerning undersampling of boundary fluxes is an argument often applied to aircraft measurements of an isolated cloud and refers to radiation escaping from the sides of the cloud that is not captured by the instruments above and below that cloud. Thus the cloud "appears" to absorb excess SW radiation because of this loss of unmeasured energy. But this isolated-cloud argument is not appropriate to our satellite-surface measurements, nor to the aircraft measurements made by Pilewskie and Valero (*3*), both of which refer to cloud systems. A study

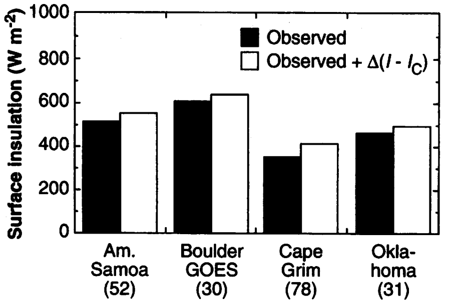

Fig. 3. Difference between $I - I_c$ for CCM2 versus the observed quantity in relation to the dayside-mean observed surface insolation. The numbers in parentheses under each site name represent $\Delta(I - I_c)$, Wm^{-2}. These data refer to dayside means and thus represent the measurement signal, in contrast to 24-hour means that are appropriate for energy budget considerations.

using a three-dimensional cloud model (*5*) concluded that the "simulation suggests that the shortwave absorptance of inhomogeneous clouds can be evaluated reasonably by means of appropriate spatial average." The point is that the "large positive and negative excursions-to-absorption" discussed by Stephens compensate when spatial averaging (*3*) or temporal averaging (*2*) is performed.

Differences between the current observations and models (as demonstrated in Fig. 3 with reference to version 2 of the National Center for Atmospheric Research Community Climate Model) are large and constitute a signal in excess of uncertainties associated with the measurements (*6*). These model-versus-observational differences, $\Delta(I - I_c)$, were evaluated so that $N - N_c$ for CCM2 was constrained to that of the observations, thus removing differences in the TOA radiation budget. The $I - I_c$ comparison also isolated cloud effects by removing model-versus-observational differences in clear-sky insolation. This comparison indicates that the model's clouds are underpredicting cloud SW absorption by overestimating cloudy-sky surface insolation relative to clear skies; we see no other plausible explanation. For the four locations, this amounts to an average surface-insolation overestimate by the traditional model of nearly 10% (Fig. 3).

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2. R. D. Cess *et al.*, *Science* **267**, 496 (1995).
3. P. Pilewskie and F. P. J. Valero, *ibid.*, p. 1626.
4. For this purpose three data sets described by Cess *et al.* (*2*) have been used: American Samoa, Boulder-GOES, and Cape Grim. The Boulder-GOES clear-sky determination was as described earlier (*2*) and was consistent with an alternate procedure utilizing GOES clear-sky identification at the TOA. The instantaneous GOES measurements were every half-hour, and the temporally colocated hourly mean surface measurements were identified as clear if GOES identified the satellite grid as clear for the three consecutive half-hourly measurements that coincided with the hourly-mean surface measurements. For American Samoa and Cape Grim, the clear-sky identification was from the instantaneous satellite measurements for the TOA and from an upper envelope of the insolation measurements, as in (*2*), for the surface. This required normalizing both TOA and surface measurements to a mean sun-Earth distance. For our present purposes the 3-year (1985–1987) American Samoa data were extended to 5 years (1985–1989), and a data processing error that affected the original data for December 1986 and throughout 1987 was corrected. Also recent data from Oklahoma have been used; these consist of colocated GOES, TOA, and surface measurements made from 5 to 27 April 1994 as part of the Atmospheric Radiation Measurements (ARM) program. The instantaneous GOES satellite measurements were hourly, and the surface insolation measurements were near instantaneous—every 15 s. The satellite measurements were averages over a 0.3° × 0.3° grid centered at the surface instrument. The surface measurements were identified as clear if GOES identified the entire grid as clear at the time of the surface measurement.
5. T. Hayasaka *et al.*, *J. Appl. Meteorol.* **34**, 1047 (1995).
6. As discussed by Cess *et al.* (*2*), the data were taken at sites where extensive attention was given to the surface instruments in terms of calibration. Also, the results shown in Fig. 1 eliminate calibration errors and long-term drifts through differencing. There are, however, other uncertainties associated with converting satellite-measured radiances to fluxes, but these uncertainties are well below the measurement-model differences shown in Fig. 3. See the paper by B. R. Barkstrom, E. F. Harrison, and R. B. Lee III [*Eos* **71**, 279 (1990)].

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Response: We address Stephens' criticisms of our report (*1*) in the order in which they appear in his comment. We find several errors in his arguments.

Stephens argues that 20% absorption by clouds, around the asymptotic limit predicted by theory (*2*), is in close agreement with the aircraft measurements in our report (*1*). However, our report states that (*1*) "maximum absorption approaches 30% of the solar constant" indicating, contrary to Stephens' statement, that the aircraft results are *not* consistent with current understanding. We have reproduced (Fig. 1) in units of fractional absorption, the measurements of figure 2 in our report.

Not all of the absorption by cloud occurs *in place of* (rather than in *addition to*) clear sky absorption, as Stephens suggests, but because there is considerable overlap in the absorbing bands of condensed water and water vapor, *some* cloud absorption occurs in place of clear sky absorption. We used this fact to adjust our estimate of cloud forcing ratio between the two aircraft to the

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