Atmospheric Radiation Enhanced Shortwave Experiment (ARESE)

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February 1998

JSR-96-310

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
February 19, 1998

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
Atmospheric Radiation Enhanced Shortwave Experiment (ARESE)

5. FUNDING NUMBERS
13-958534-04

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
The MITRE Corporation
JASON Program Office
1820 Dolley Madison Blvd
McLean, Virginia 22102

8. PERFORMING ORGANIZATION REPORT NUMBER
JSR-96-310

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Department of Energy
Research and Development
Defense Programs
Washington, DC 20585

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
JSR-96-310

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE
Distribution Statement A

13. ABSTRACT *(Maximum 200 words)*

This report has been prepared in response to a request by the U.S. Department of Energy to review and assess the data and data processing being undertaken in conjunction with the Atmospheric Radiation Measurement Enhanced Shortwave Experiment (ARESE). This experiment is a portion of theAtmospheric Radiation Measurement (ARM) of the DOE. The ARM measurements have many purposes, of which two primary goals are (1) to check the accuracy of current knowledge of physical processes occurring in the atmosphere, and (2) to check the accuracy of current General Circulation Models (GCM) of the atmosphere. Purpose (1) is to check the physics; purpose (2) is to check the computer codes.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102

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1 INTRODUCTION

This report has been prepared in response to a request by the U.S. Department of Energy to review and assess the data and data processing being undertaken in conjunction with the Atmospheric Radiation Measurement Enhanced Shortwave Experiment (ARESE). This experiment is a portion of the Atmospheric Radiation Measurement (ARM) program of the DOE. The ARM measurements have many purposes, of which two primary goals are (1) to check the accuracy of current knowledge of physical processes occurring in the atmosphere, and (2) to check the accuracy of current General Circulation Models (GCM) of the atmosphere. Purpose (1) is to check the physics; purpose (2) is to check the computer codes.

The JASON study participants heard and read reports of observations addressed to both areas as they pertained to the ARESE program of experiments and data analysis focused on issues involving our understanding of the absorption, reflection, and transmission of solar (short wave) optical radiation. The observations in both areas are high in quality but fragmentary in scope, good enough to find discrepancies but not good enough to identify the causes of the discrepancies. In area (1) the reports were clear, especially those presented by Professor Ackerman and his colleagues, and the additional measurements required to resolve the discrepancies and understand the physics are well defined. In area (2) the reports were more obscure and confusing, because the interpretation of GCM results is obscure and confusing, and it is unlikely that future ARM measurements by themselves will dissipate the confusion.

Our study this summer concentrated on the state of the comparison between models and measurements of the absorption of solar (short wave) optical radiation by the atmosphere and the Earths' surface under both clear and cloudy skies. The incoming short wave (approx. 0.3 micron–5 micron in wavelength) radiation from the Sun provides the forcing for atmospheric circulation, oceanic heating, and evaporation from the oceans. An understanding of the short wave radiative forcing term is therefore critical to formulating a robust model of the climatic properties of the planet.

During the summer 1996 JASON study various analyses of many data sets were presented and discussed by experts in the field. Although we have made considerable efforts to follow these discussions, we do not consider it to be our task to resolve these various conflicting points of view. Rather we have tried to formulate recommendations for progress that take into account the present uncertain state of the field.

2 PHYSICAL MODELS OF THE ATMOSPHERIC COLUMN

Our study concentrated on the state of comparison between models and measurements of the absorption of solar (short wave) optical radiation by the atmosphere and the earths surface under both clear and cloudy skies. The incoming short wave (approximately 0.3–5 micron in wavelength) radiation from the sun provides the forcing for atmospheric circulation, oceanic heating, and evaporation from the oceans. An understanding of the short wave radiative forcing term is therefore critical to formulating a robust model of the climatic properties of the planet.

A first-order understanding of the atmospheric column radiation budget can be obtained by comparing measurements made at the Oklahoma ARM site to empirical fits parameterized as a function of a few important parameters of the column, such as the column liquid water content. These empirical fits are represented by the model of Fu and Liou and other similar models, and the parameters of the model have been determined by a variety of measurements (liquid water content, water vapor, aerosols, clouds, etc.) whose exact extent has not been made clear to us. However, the results are that the model reproduces a large part of the observed variability of net total atmospheric and Earth-surface absorptions; those absorptions vary from about 20% to 80% and the model reproduces those different values to within about 5% on the basis of liquid-water content, water vapor, and a few other minor parameters. That the model agrees with empirical observation is not proof, of course, that all relevant parameters or processes have been accounted for.

The typically 5% discrepancies have two components; a statistical variability AND a disagreement in the mean. And the claim is made that disagreements at this level of 5% have very significant consequences when translated to their effects on GCMs. These claims, however, at the present time are just that, claims, and not established results.

Several recent analyses have attempted to isolate these discrepancies in various bins of parameter space, where the parameter space spans the quantities considered important up until now. For example, some analyses have attempted to make the case that the discrepancies appear for observations with cloudy skies, while others have insisted that there are discrepancies in the clear-sky measurements as well. Since clouds play such a large role in determining the radiation budget striking the surface of the Earth, a discrepancy between models and measurements of the optical properties of clouds would be very significant. Other researchers, however, have claimed that the discrepancy is not associated with the properties of clouds but instead is related to components of the atmosphere other than clouds, for instance, aerosols, water vapor, or other molecularly-based trace absorbers. Still other workers maintain that the instrumental measurement uncertainties are sufficiently large that no disagreement between models and observations has been proven definitively to date under either clear or cloudy conditions.

The following four sections summarize the analyses to which we were exposed this summer from the ARM program. We have divided the analyses into categories by spatial and temporal scales of averaging. The spatial averaging scale ranges from the local scale of an individual pyronometer observation to the global scale of hundreds of land sites within the Global Energy Budget Archive (GEBA) monitoring program. The temporal averaging scale ranges from several years available within the GEBA program to a few minutes in an airplane-based cloud observation program.

3 GLOBAL SPATIAL SCALES AND MULTIYEAR TEMPORAL SCALES

The GEBA is a data set in which downwelling insolation is available for hundreds of land-based ground stations over periods of several years. At some locations, surface albedo measurements are available, and therefore net surface radiative fluxes are available. These surface albedo measurements also serve as ground truth for development of an inversion algorithm to enable monthly mean surface albedo measurements to be determined from satellite observations. Satellite observations have been performed at many locations for the period of concern using both ERBE (Earth Radiation Budget Experiment) broadband radiative instruments and GOES narrowband detectors. The GOES–6 and GOES–7 satellites have been calibrated relative to ERBE at several locations, although there is concern regarding the robustness of the inversion algorithm in retrieving the surface albedo at certain sites.

Since ERBE data provide the net globally averaged flux at the top of the atmosphere (TOA), it is possible to compare the predictions of the surface radiation budget from a number of GCM's to the values observed experimentally from the GEBA sites and extrapolated to global mean net surface insolation values. These data are summarized in Table 1. They clearly show a difference, on the order of 20 W/m^2, between atmospheric absorption predicted by the CCM2 and CCC GCM models and that inferred from the GEBA data set, regardless of whether the monthly mean surface albedo and net TOA flux values are measured using the ERBE or GOES satellites. Such a comparison indicates that more short wave radiation is being lost between TOA and ground level (e.g. absorbed in the atmosphere) than is expected from a prototypical GCM model.

Table 1. GEBA DATA

	OBSERVATIONS		MODELS	
	GEBA-GOES	ERBE	Model CCM^2	CCC
Reflected TOA	101.2	101.2	94.3	111.3
Surf. Net	142.0	157.0	180.6	172.0
Atm. Absorption	98.1	83.0	67.6	58.0

It is also possible to regress the GEBA data against surrogates for cloud coverage, to empirically investigate whether any correlations are evident between the apparent excess absorption (unaccounted for discrepancy between TOA and ground-level values) and the mean cloud coverage above the various reporting GEBA stations.

Arking has performed an independent analysis of the GEBA data.[1] He compared the atmospheric absorption of short wave solar radiation predicted by a model (GEOS-1 from Goddard) with the results of the GEBA data set, when regressed against various parameters of interest (e.g. water vapor, cloud fraction, local mean monthly albedo.)

For this study, observations were only used at locations where the following five quantities were all available:

1. Downward solar irradiance at 173 sites over 12–24 months, from the GEBA data archive.
2. Net flux at the TOA from ERBE.
3. Monthly mean surface albedo measurements as retrieved from satellite measurements and an inversion algorithm from the Surface Radiation Budget Climatology Project (SRB). This is the same quantity used to obtain the net monthly mean surface flux at the sites of concern in the GEBA/ERBE or GEBA/GOES analysis presented above.

4. Mean cloud cover fraction, as measured from the International Satellite Cloud Climatology Project (ISCCP).

5. Total column water vapor, also from ISCCP.

Arking compared the atmospheric absorption values for the data for the various sites and those computed from the GEOS-1 model. As can be seen in Figure 1, the model shows less short wave radiation absorbed in the atmosphere than is indicated by the observations, and the values correspond to discrepancies of 25–30 W/m^2, in rough agreement with the previous numbers.

Arking then regressed the data against two surrogates for cloud coverage. The first measure of cloud coverage is obtained from the ISCCP (International Satellite Cloud Coverage Program) narrow-band weather satellites, which produce data that can be supplied to a retrieval algorithm in order to produce values of the monthly mean fractional cloud coverage over the various GEBA sites. In addition, the difference between the monthly mean albedo and the monthly mean clear sky albedo over the various sites has been employed as an alternative surrogate to represent the monthly mean cloud coverage.

Figure 1 shows the results of these regressions, both for the predictions of the model and for the observational data. One sees that this procedure reveals little correlation of the atmospheric absorption with cloud cover surrogates (i.e. the regression lines have nearly zero slope). In fact, it would appear from these data that there is a systematic difference that is roughly independent of cloud coverage; i.e. that the difference between the models and experiments is some property of the atmosphere other than clouds. A regression against the total monthly mean column water vapor, again retrieved from the ISCCP observations through an algorithm, showed a better correlation with the atmospheric absorption data, suggesting that the discrepancy between models and observations might, at least in part, be associated with

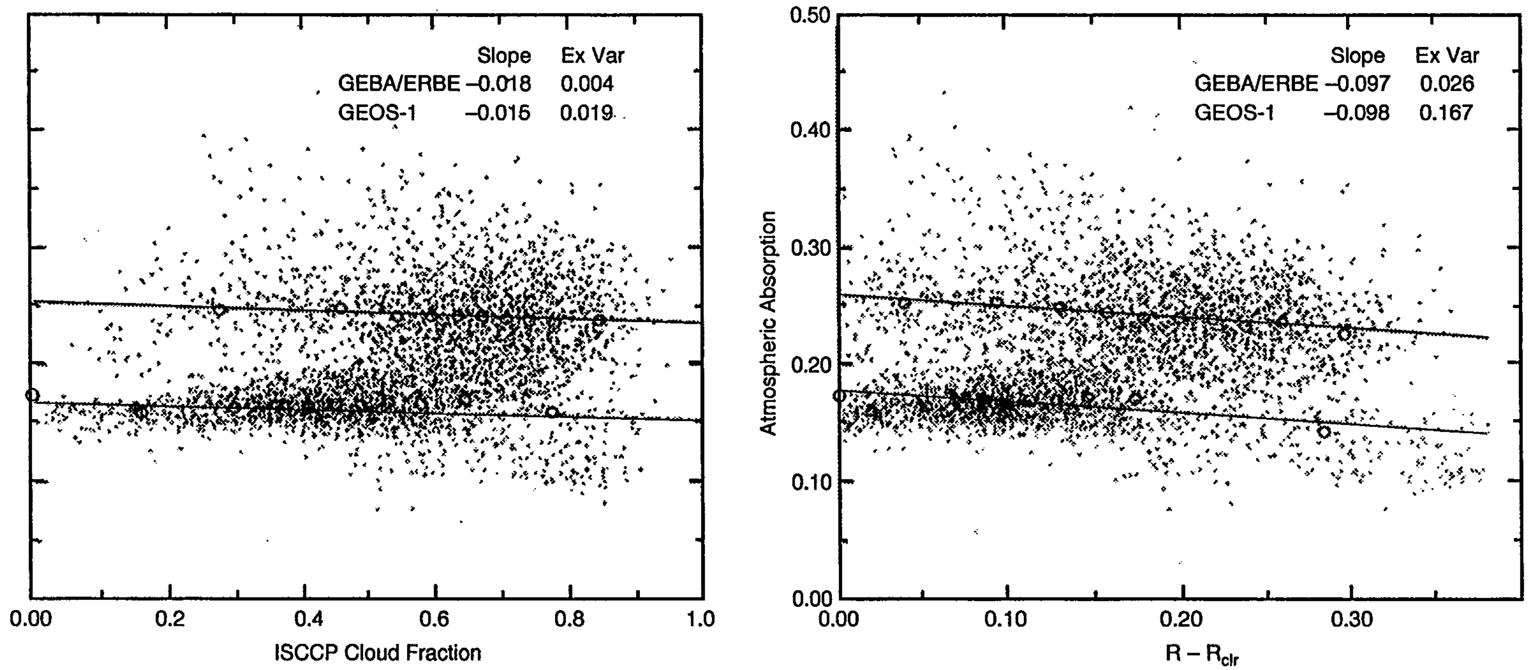

Figure 1. Scatter plot of atmospheric absorption against ISCCP cloud fraction (left side) and against ERBE all-sky minus clear-sky albedo at the top atmosphere ($R - R_{clr}$, right side), for the GEBA/ERBE data set using the average of the surface albedos of Pinker and Staylor (red), and for the GEOS model (blue). Data points are plotted only where surface albedo satisfies filter F1. Solid lines are derived by linear regression, with slopes and explain variances shown. Circles are values obtained by binning, using 10 bins, with an equal number of data points in each bin. Circle on ordinate axis indicate GEOS-1 model clear-sky absorption.

water vapor or with an optical property that is correlated to the water vapor content above an observational site. Based on these data, then, it appears that there is a discrepancy between the models and observations of approximately 20 W/m^2, but that the source of the effect may be more closely related to water vapor than to cloud cover, when averaged over global-scale spatial scales and multiyear temporal scales.

4 LOCAL SPATIAL SCALES AND MULTI-YEAR TEMPORAL SCALES (THE WARM POOL)

Ramanathan et al. [2] analyze the situation over the Pacific Warm Pool (WP), a region of a few thousand square miles, and they use data spanning about two years. Although we present the WP local results before those of Cess et al., because the WP results are averaged over a longer time scale, we should say that the WP results are less impressive in establishing an effect than the observations of Cess et al. that are summarized in the next section.

Ramanathan et al. consider a simple energy balance at the ocean surface, within the mixed layer:

$$\text{Net Heating [Q]} = \text{Average Solar Heating}[S_a + C_s(S)] \tag{4-1}$$

$$- \text{Upward Loss due to Radiation, Evaporation and Turbulence}[F + E + h]$$

$$- \text{Downward Loss into the Ocean [D]}$$

The driving term in Equation (4-1), the Average Solar Heating, is split into two components: the Clear-sky solar heating (S_a), and the correction term $C_s(S)$ ("Short-wave cloud forcing" at the surface) that accounts for how the presence of clouds affects the solar heating at the surface, on average.

All the terms in this expression are spatially averaged over the WP. The spatial averaging is intended to allow an essentially one dimensional treatment: lateral transfer of heat out of the warm pool is ignored to first order. This approach is supported by the evidence [3, 4] that the Downward Loss into the Ocean [D] (also called "dynamical heat transport"), which includes lateral advection by ocean currents [D_a], is small (20 W m^{-2}) for the Pacific warm pool (two terms are considered to make up the Downward

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Loss [D], downward advection [D_a1 and sideways entrainment [D_e]: D = D_a + D_e).

The terms in Equation (4-1) are also averaged over some suitably long time period of at least a few years [5]. This point is crucial because the authors need to be able to set Q = 0 for their approach to work, yet it is not clear how long an averaging period is actually required in order to justify this assumption. The authors realize this problem and state (p. 500) that their quoted uncertainties provide only rough estimates of true 1σ errors because of the short time span available for constraining some of the variables in Equation (4-1). This problem is especially severe for two of the variables, S_a, and F, the former being the largest in magnitude within Equation (4-1).

Ramanathan, et al.'s primary contribution is in evaluating the largest term, S_a, and in applying Equation (4-1) to determine C_s(S). The other terms are relatively small, as indicated by the following summary which gives Ramanathan, et al.'s values and their estimated uncertainties for each term:

$$\begin{aligned} Q = 0(\pm ?) = \quad & S_a[275(\pm 5)] + C_s(S) \\ & -F[45(+10,-0)] - (E+h)[110(+20,-15)]D[20(+10,-0)] \end{aligned} \tag{4-2}$$

Equation (4-2) includes Ramanathan, et al.'s Equations 1–3 and Figure 1. Note the asymmetric uncertainty estimates, which document the authors' attempt at getting a conservative estimate for the one unknown variable, C_s(S).

In this approach S_a is not actually measured, but is derived from a model applied to monthly-averaged measurements made by ERBE at the top of the atmosphere ([2] and [13] therein). The value used by Ramanathan, et al. includes a correction for surface albedo, which appears to be small and relatively well-constrained.

However, obtaining S_a also requires modeling transmission through the atmosphere (from the top of the atmosphere to the surface). Li, et al.'s transfer function is used for this purpose [6],[7]. Ramanathan, et al. emphasize that by using their modeling approach they correct for the humidity present in the atmosphere on average (cloud-bearing) days. Furthermore, they show that their approach does reproduce surface observations for the Pacific warm pool on clear days. Therefore, the authors have tried to account for at least some of the effects discussed by D. Sowle, including possible extra absorption by air on cloudy days, and have made a reasonable attempt to estimate S_a such that adding $C_s(S)$ yields the true solar flux into the ocean surface on average days.

Ramanathan, et al. compare their best estimate for $C_s(S)$ [100 (+45, -20) W m^{-2}] with values measured at the top of the atmosphere [C_S(TOA) = 66 ($\pm$ 10?) W m^{-2}] (in both cases, these are "upward" fluxes). These numbers imply an atmospheric absorption that is larger in cloudy skies than in clear skies by an amount on the order of 5%. We will see in the next section that this is in disagreement with models.

Altogether, Ramanathan, et al.'s approach is good in that it uses a simple method (therefore robust, in principle) to estimate the "short-wave cloud forcing" [$C_s(S)$]. Also, they have been conservative in systematically trying to minimize the value they obtain for $C_s(S)$, as is reflected by the asymmetric uncertainties in Equation (4-2).

The largest area of uncertainty in the analysis relates to the estimated error on S_a. The quoted uncertainty ($\pm$ 2%) seems very small, given: i) the differences quoted for S_a even on nominally clear days (271–306 W m^{-2} in Table 1; granted these are for different locations and temporal scales), ii) the authors' comments on the potential lack of a long enough time series to ensure true averaging, and iii) the fact that S_a is calculated via a model. On the last point, top-of-the- atmosphere values for solar heat fluxes quoted elsewhere ($\sim$ 340 W m^{-2}) indicate that a large correction ($\sim$ 70–100 W m^{-2})

is required to determine S_a, so it seems probable that the true uncertainty is much larger than 5 W m^{-2}. An uncertainty of at least $\pm$ 15 W m^{-2} seems a naive but not-unreasonable guess, knowing nothing else.

A secondary concern bears on the Evaporative heat loss [E], the second largest term in Equation (4-2). Again, the quantity is calculated [8] from actual measurements, consisting of 2 years' worth of TOGA-TAO buoy observations of sea-surface temperature (SST), boundary-layer temperature, humidity and "winds". Inspection of Figure 2 raises a serious point of concern, however, in showing that daily and hourly averages of "Evaporative flux" [E] estimates differ by 10–15 W m^{-2} on average over a 5-month period. The degree of scatter shown in the figure makes one wonder how reasonable it is to represent E by an *average* in the first place, let alone whether the best value is actually used in Equation (4-2). Similar concerns arise with the other terms in Equation (4-2), but the problem with E is evident from the discussion in the paper and is important because of the large magnitude of this term.

If one accepts all of the quoted values and uncertainties of the quantities in Equation (4-1), there is a possible effect at the 1σ level (but not at the 2σ level). Furthermore, the effect goes away if the uncertainties are incorrectly estimated in any of the following ways: 1) $Q \neq 0$, or other variables are unreliable, due to insufficient temporal sampling; 2) S_a is more uncertain than quoted because of variability in the observations being averaged or because of uncertainties in the model required to calculate S_a; or 3) estimates are not conservative enough (in fact, simply making the quoted uncertainties symmetric all but removes the effect). Of these, item 2 seems especially important, given the discussion above as well as the independent arguments presented in Arking's analysis of the GEBA data.

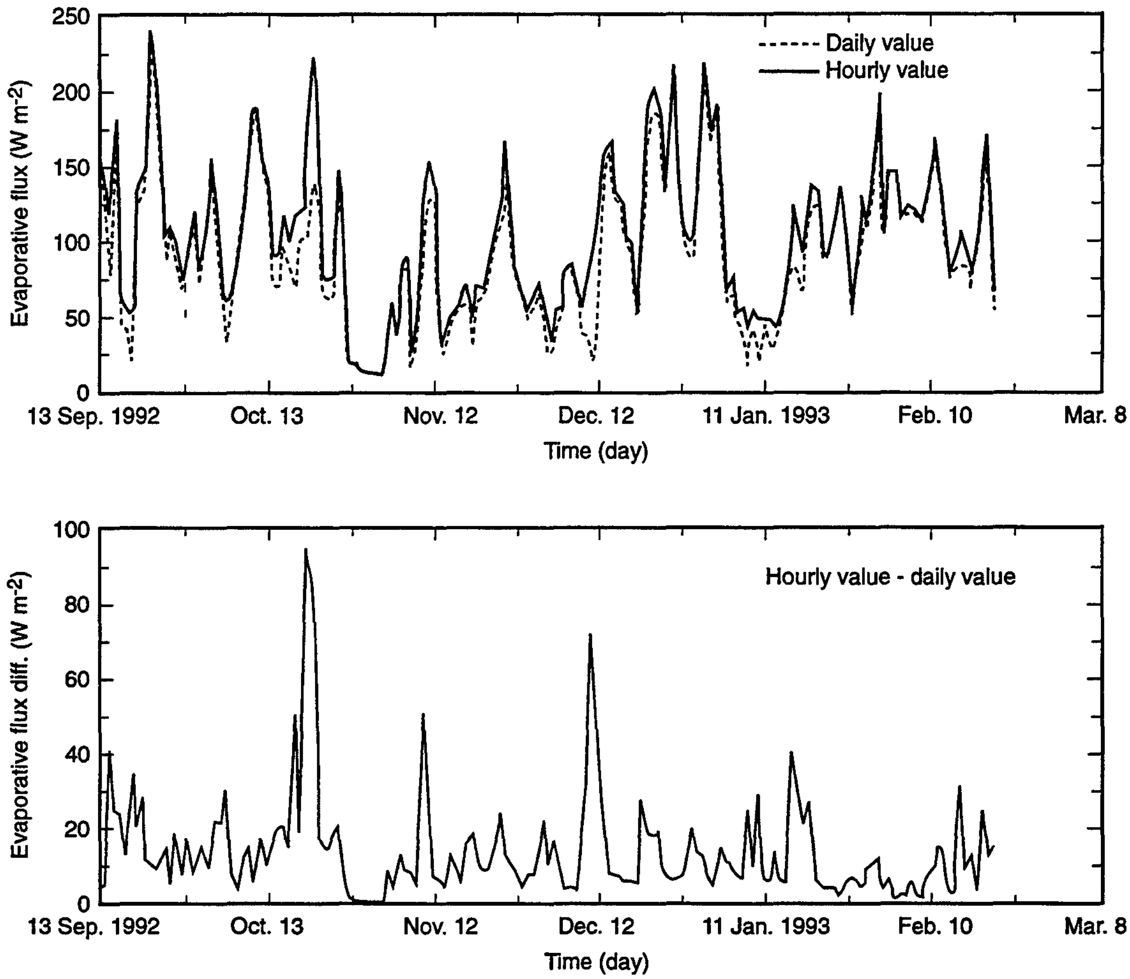

Figure 2. Time series of evaporative heat flux (upper panel), computed from hourly data (solid line) and daily averaged data (dotted line), and their difference (hourly — daily, lower panel).

5 LOCAL SPATIAL SCALES AND MONTH-LONG TEMPORAL SCALES

The Oklahoma ARM site provides an important set of measurements that are extensive in type, and apply to a specific location so that physics effects can be observed directly. Let us form an overview of the data at this site before moving on to the analysis of Cess et al. for the purpose of comparing models with the measurements.

The data from the Oklahoma site have been put on the World Wide Web, where it is labelled as CAGEX. The CAGEX data can be used to form averages and to determine thereby the radiation-energy balance within the atmosphere for clear sky or all sky conditions. It will be most instructive to put the information in terms of the total solar insolation as one hundred percent, with other measurements expressed as a percent of this value. Thus we avoid using watts per square meter, and we avoid having to distinguish between diurnal mean and day-side mean.

We first refer to the measured fluxes (CAGEX data) at the Oklahoma site during April 1994. The TOA albedos of 20% and 31% for clear sky and all sky, respectively, mean that clouds reflect more energy back into space than does the clear sky atmosphere. For all sky conditions, 11% less energy enters the atmosphere than for clear sky conditions. Individual values of the albedo for clear sky conditions cluster between about 15% and 25% (average: 20%), while those for all sky conditions are spread between about 20% and 80% (average: 31%).

At the surface of the earth, in clear sky conditions, 61% is absorbed (and therefore leaves the atmosphere), while in all sky conditions only 38% is absorbed. The combination of the entering flux from the TOA and the flux leaving the Earth, when subtracted from 100%, leaves a remainder which must be the amount of energy absorbed in the atmosphere. Although these numbers have not been quoted in Cess et al.,[9],[10] we quote them here based on the available data from the SGP ARM site during the IOP in April, 1994. For clear-sky conditions during these observations, 19% of the incoming solar radiation is absorbed in the atmospheric column, while for all sky conditions, 25%, or 6% more, is absorbed.

A useful number to keep in mind is that the albedo at the Earth's surface in Oklahoma is 20%: a number that has been measured both in clear sky and full-sky conditions. Another set of numbers not given in the figure involves the breakdown of the downward flux at the surface into direct and diffuse components. In clear-sky conditions, the downward 76% is split 65/11, between direct and diffuse components, while in full-sky conditions, the downward 48% is split 29/18.

Figure 3 shows values for these atmospheric conditions that are computed from the CCM2 GCM. Mean values of the column water vapor have been used, and mean values of the clear sky and all sky absorption are therefore produced by the model. There clearly appears to be a discrepancy between the model and observations.

Additional data supporting a cloud anomaly has been obtained by Cess and co-workers at the Boulder site. The clear skies scenes in such data have been assigned by the satellite, as suggested by others, and a set of consistent values are obtained which again imply that the observed atmospheric absorption in cloudy skies is significantly larger than models generate.

Perhaps equally significant is the excellent agreement between the radiative transfer models and observed <u>clear sky</u> column transmittances at the Boulder site. This significant observation has not yet been published, and the data are not fully documented in the preprint that was made available

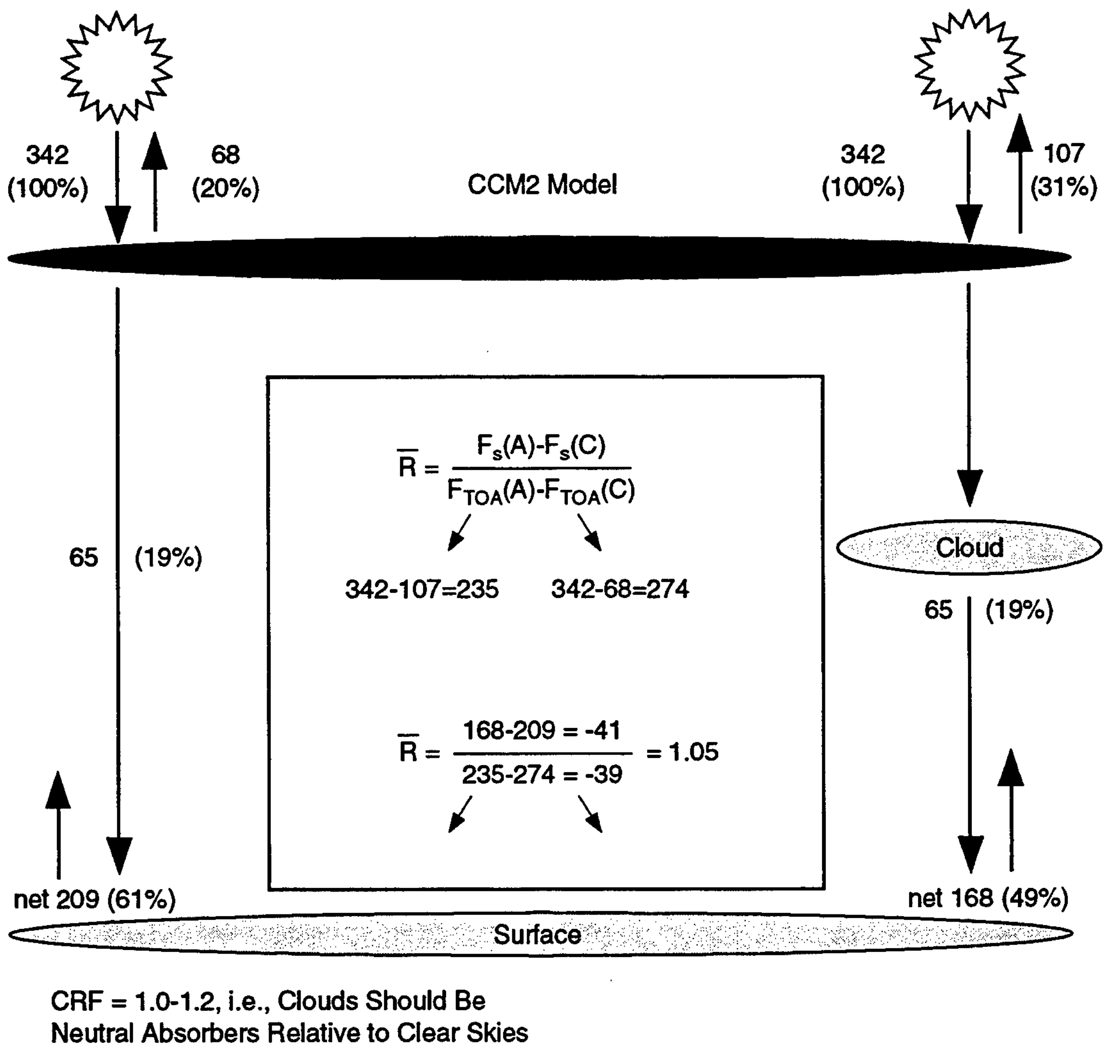

Figure 3. Summary of typical values from a GCM with values in W/m^2, in clear sky (left) and all-sky (right) conditions.

at the time of the JASON briefing, but are summarized schematically in the bar graphs of the preprint and have been orally confirmed in follow-up conversations between the JASONs and R. Cess. This finding is important since it would imply that the clear sky anomaly at the ARM site identified by some, but not all, workers may be due to some effect that is specific to that location.

After the summer study ended, however, a more recent communication to the JASONs from T. Charlock indicated that the same clear sky discrepancy that has been observed at the SGP ARM site is also apparent in his analysis of Boulder data.[11] If this finding holds up, it seems to imply that there is a problem with the description of the clear sky data that warrants careful, serious analysis of all relevant data sets. An additional concern has been raised by Imre et al., [12] who have questioned an analysis of the CAGEX all sky data in terms of clear sky assignments based only on the maximum observed transmittance instead of based on satellite scene identification data. Imre et al. claim that the latter is more reliable, because it reduces any bias towards the "clearest of clear skies" that is introduced by only considering observations with maximum column transmittance. Imre et al. claim, however, that use of the satellite-based scene identification procedure reduces or perhaps even eliminates the magnitude of the discrepancy between the models and experimental data for cloud forcing while still indicating a discrepancy in clear sky conditions when uncertainties in the experimental data and in the models are both considered.

Cess et al. analyze a number of other sites around the world (Wisconsin, France, and Germany) and they identify high atmospheric absorption in cloudy-sky conditions of the same magnitude as observed at Oklahoma and Boulder.

6 LOCAL SPATIAL SCALE AND SHORT (MINUTES TO HOURS) TEMPORAL SCALES

Francisco Valero has conducted two experiments involving the simultaneous flights of two airplanes above and below a cloud region. The first experiment is the only one for which we have detailed information [13], the second is still in the analysis phase.

The first experiment was conducted over the "warm pool" in the tropical Pacific. It consisted of flying an ER-2 aircraft above the clouds at 20 km altitude almost directly above either a DC-8 or a Learjet that was flying at nominally about 10 km altitude (actually varying from 8–12 km) under the cloud layer. The upwelling and downwelling short wave fluxes were measured by both aircraft. Many hours of data were obtained.

Let C_S be the cloud forcing at 10 km; that is, C_S is the difference between the cloudy sky and clear sky net flux at 10 km. It is thus the difference between absorption by the surface and lower atmosphere under the clouds and the same quantity under a clear column of air. Correspondingly, C_T is the difference between absorption by the cloudy total column (up to 20 km) and surface and that of a clear total (up to 20 km) column atmosphere and surface.

Thus

$$C_T = C_S + A(\text{cloud}) - \text{A(clear)} \tag{6-1}$$

where A is the absorption by the column between 20 km and 10 km.

The first question is: do clouds absorb significantly more radiation than clear air? To answer this it is necessary to obtain A(clear). This was done by assuming that the maximum measured net flux at each solar zenith angle is the clear air value.

With this assumption A(clear) is about 60 W/m^2, nearly independent of zenith angle. (The uncertainty is estimated at 5 W/m^2, but the basis for this estimate was not explained. In addition, there are some measured points lower than A(clear); they are attributed to additional flux from scattering off the sides of clouds.)

The measured cloud absorption A(cloud) between 10 and 20 km increases relatively strongly with solar zenith angle and has an average value of 165 W/m^2; thus clouds absorb much more than clear air.

Using these values and the measured value of C_T = -113 W/m^2, ratio C_S/C_T can be estimated to equal 1.68.

The second question is how well these results agree with models. Because models use quantities measured at the Earth's surface, not at 10 km, this requires extrapolating from 10 km to 0 km.

It is assumed that the lower 10 km of the total column contributes no additional absorption. This assumption is called "plausible", and is justified by the authors through the statement that the water vapor bands are already saturated at 10 km.

A(clear) is extrapolated by using the LOWTRAN7 radiative transfer model. This model gives A(clear) = 100 W/m^2. Using these numbers one gets C_S/C_T at the surface to be 1.58. All theoretical calculations produce $C_S/C_T = 1$; the "experimental" analysis of Cess et al. and Ramanathan et al. give values of C_S/C_T near 1.3 to 1.4.

The second "stacked airplane" experiment was conducted in association with the ARM site in Oklahoma. It used an Egrett airplane at 13 km altitude and, almost directly below, a Twin Otter at 1.7 km. Both planes carried the same suite of instruments. Many hours of data exist. The raw absorption data is displayed instantaneously, with a 10 second averaging, and with 180 second averaging. We have no detailed written analysis of these results, but the verbal summary given in our briefing says they are consistent with those from the tropical Pacific.

The existing GCM cloud parameterizations do not lend themselves well to describing the absorption by an individual cloud formation, however. Instead they parameterize clouds in terms of the column liquid water content and some mean, plane-parallel cloud model of optical properties; thus, there is no expectation that the model would describe accurately individual all-sky observations, which would be expected to encompass situations of various cloud heights and cloud types. We thus conclude that additional work would be required to judge the significance of these airplane measurements with respect to the GCM cloud parameterization algorithms that are currently being used.

7 AEROSOL EFFECTS

Ackerman et al. have carried out observations and an analysis of anomolous absorption effects similar to those of Cess et al. Ackerman takes the point of view that clouds are not the culprit, because no measure of cloud fraction (other than the binary choice of clouds or clear) shows any correlation with the anomalously high atmospheric absorption indicated by their measurements.

Ackerman et al. measured, at the ground, both parts of the total downward-moving short-wave flux integrated over a hemisphere: the direct solar flux (within a narrow cone about the sun direction): and the diffuse flux, (the downward flux lying outside that cone). The measurements were made concurrently in several frequency bands. The water vapor profile was determined from radiosonde and microwave radiometer data. The observed solar extinction obtained from the direct flux data could not be fully accounted for by water vapor and other well known molecular constituents in the atmosphere. The discrepancy was presumed to be caused by aerosols. Several different kinds of aerosols were considered. For each type of aerosol, the otherwise unmeasured aerosol concentration was adjusted to make the solar extinction coefficient agree with the experimental observations. Thus the aerosol concentration was empirically adjusted to fit the direct flux data. The claim is that the various types of aerosol considered (sulphate, mineral dust, soot) span the range of realistic possibilities, but there is no way to fit the observed diffuse fluxes at all the wavelengths studied. The observed diffuse flux was smaller than the model ones by roughly 30–50 percent!

Proposed explanations of these observations include the following:

1. The aerosol types may have been misidentified and/or their scattering

and absorption cross sections may have been inadequately modelled in the literature. For the aerosols considered, the ratio of downward scattering into the diffuse zone relative to direct beam absorption would have to become smaller than has been expected theoretically when aerosol abundance is inferred from beam extinction. Extinction in the direct beam depends on what we may call the effective total cross section, which is the sum of two terms: $s_T(\text{eff}) = s_{inel} + s_{inel,a,}$ where s_{inel} is the inelastic cross section, and $s_{el,a}$ is that part of the elastic cross section that corresponds to photons scattered outside of the forward cone accepted by the solar photometer. (Photons scattered into that cone do not count as being absorbed nor do they contribute to the diffuse flux.) The diffusely scattered flux depends on $s_{el,b}$, that part of the elastic cross section that corresponds to elastic scattering into the diffuse zone. In this notation, the quantity that needs to become smaller in aerosol models is the ratio $S_{ei,b}/S_T(\text{eff})$.

Can one imagine plausible aerosols not included in present models for which this ratio is sufficiently reduced to reconcile data and expectations? Suppose, for example, that an unexpectedly large population of extremely small aerosol particles ($R << \lambda/2\pi = 0.1\ \mu$) is also present but has not been included in models. These additional particles would Rayleigh scatter half of the scattered radiation into the backward hemisphere; then only about half of the photons scattered out of the incident beam would appear in the diffuse radiation. (The presumably more realistic aerosols used in current models are larger in radius and scatter mainly into the forward hemisphere.) But, with the much smaller aerosols the deficiency in the diffuse beam fraction would grow roughly as the 4th power of frequency. The observations do not seem to fit this additional small aerosol component hypothesis.

The anomaly would be mitigated if the aerosol contained a substantial component possessing a ratio of inelastic to elastic cross section that is larger than for the aerosols considered in the models. Consider Figure 4, which is taken from Ackerman's briefing charts. It describes the diffuse radiation observed during one of the two days that were studied. The two upper curves refer to the model prediction for clear sky without any aerosol at all. (There are two curves because there are two instruments.) The two lower curves refer to a model with mineral dust aerosol, in concentrations adjusted empirically to account for the observed extinction of the direct radiation with the differences between the observed and the computed diffuse flux plotted in the figure. As the curves show, for this particular day the observed diffuse flux agrees closely with what is computed for the sky without any aerosol at all (i.e. the irradience difference is near zero). But (not shown here) the direct beam extinction does not agree with expectations when no aerosol is included. When mineral dust aerosol is introduced and its concentration empirically adjusted to fit the observed extinction (optical depth about 0.05), the diffuse flux is in error, as shown by the lower curves, with too much forward hemisphere elastic scattering predicted relative to the observed extinction. The presence of a predominantly inelastic absorber in the aerosol on this day would seem to be more compatible with the data.

2. The standard codes used for water vapor absorption may be in error for spectral regions very far from those in which absorption has been directly measured. Reliable extrapolation to regions far from the center of an absorption line requires an adequate description of the time history of the interaction of a water molecule during collisions with N_2, O_2, H_2O. A characteristic collision time exceeds 2×10^{-13} sec. Correspondingly, the idealized Lorentzian shape is expected to fail for distances greater than about 25 cm^{-1} away from an absorption line.

   This is less than the separation between rotational lines of the water molecule. It would be extremely useful, therefore, to test the current

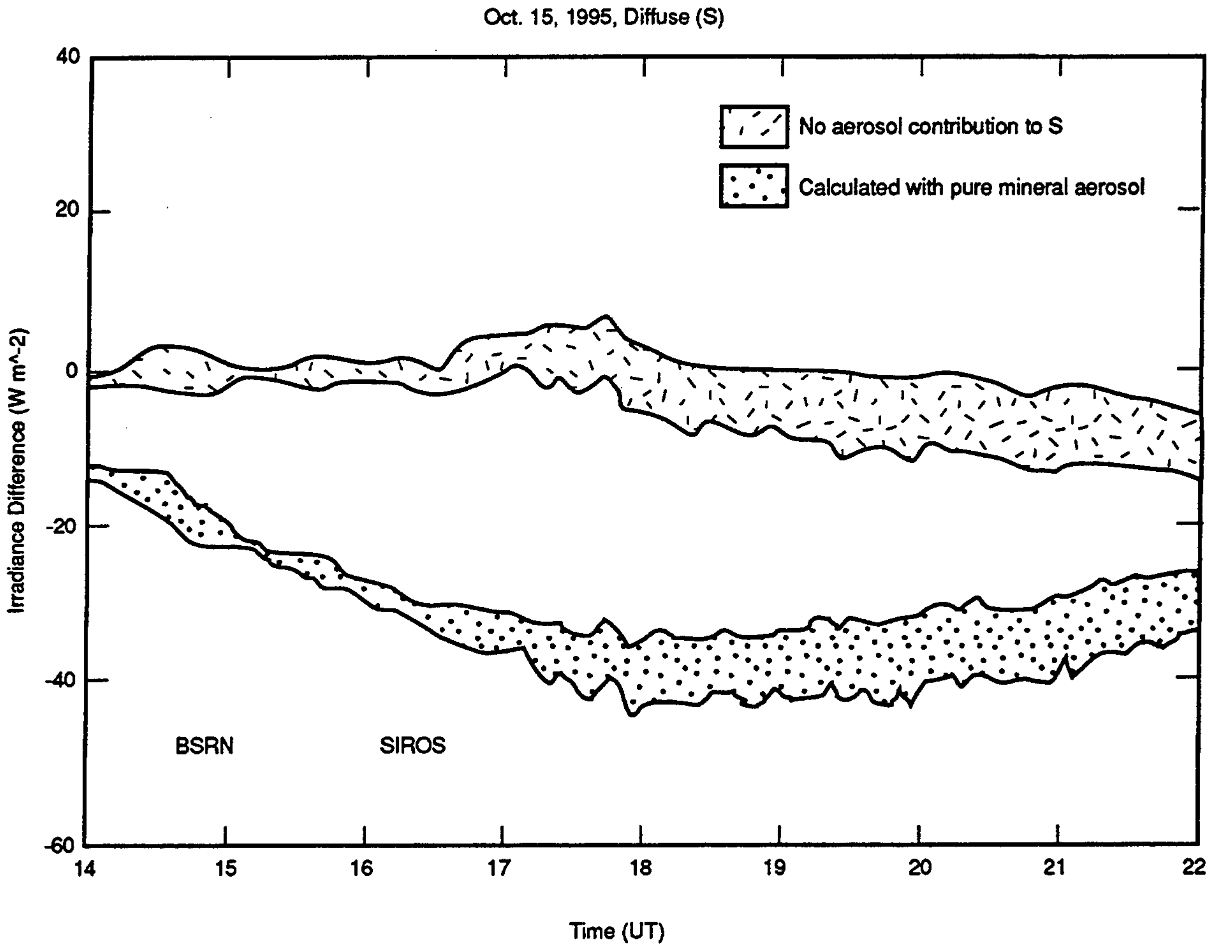

Figure 4. Measured scattered short wave radiation (s) — calculated scattered short wave radiation, when aerosol abundance is adjusted to fit observed attenuation of the direct solar incidence at the ground. The water vapor contribution to absorption is calculated from standard codes and measured M (1.1 g cm^2).

shortwave absorption codes and to improve them on the basis of direct laboratory measurements. Photoacoustic techniques, which have succeeded in detecting absorption at the level of 10^{-10}, seem to offer a promising approach to this important enterprise.

3. Dimers and more elaborate polymers of water may be making important contributions to the absorption of short wave radiation, whether the polymers are stable or transient (in the latter case they are really part of the dynamics of water-water collisions). Much of the water vapor at high altitudes, even in cloudless skies, may be near saturation or even, at times, supersatured. Such conditions favor polymer formation. Present laboratory absorption experiments generally involve the heating of water vapor to such high temperatures that condensation is minimal. But this is a condition that inhibits polymer formation. Polymers are not included in presently used water vapor absorption codes.

4. Ackerman has suggested the possibility that the atmosphere contains one or more molecular species that have hitherto been disregarded in radiation transfer studies. According to his analysis of the data, in order to fit all the observations the effective total cross section must grow by an order of magnitude as the wavelength varies from 1.0 to 0.4 microns. He suggested NO_2 or organic molecules as possible candidates. The optical sum rule can be used to place bounds on possible abundances of such species. Even for a molecular absorption band that happens to saturate the absorption sum rule limit over the short wave spectral range, the required atmospheric number density of the absorbing molecules would have to exceed about 1 ppm. This is larger than the concentration of any known "minor" species in the atmosphere (the limit is approached only by CH_4). (For a nominal electronic absorption, band over this region, a concentration as small as 1 ppb could be interesting.) There are quite a few species that might be looked at

more carefully for this role, including NO_2.

5. Perhaps — we hesitate to raise this possibility — the instrument calibrations are in error.

The approach taken by Ackerman and colleagues is a very productive one. We believe that it should be elaborated and replicated at other sites. Especially important would be the development of techniques to establish the optical properties of aerosols by direct detection rather than relying on empirical manipulation of input parameters to a model.

At present, the clear sky anomaly is based on a division of the surface radiation into two categories, direct and diffuse. We would achieve much greater insight into this phenomenon if the radiation could be measured more finely as a function of angles, i.e. if the radiant intensity could be sorted into a larger number of solid angle bins. Radiation transfer models should be subjected to this more stringent test with data being collected at a number of sites over a variety of atmospheric conditions.

8 RECOMMENDATIONS

The ARM measurements have many purposes, of which two primary goals are (1) to check the accuracy of current knowledge of physical processes occurring in the atmosphere, and (2) to check the accuracy of current General Circulation Models. Purpose (1) is to check the physics; purpose (2) is to check the computer codes. In our judgment, both purposes are equally important. Recent measurements have revealed significant discrepancies between theory and observation in both areas. But ARM, in general, and ARESE in particular, has different capabilities in the two areas. In area (1), the primary responsibility for resolving discrepancies lies with the ARM community. In area (2), the primary responsibility lies with the GCM community. We recommend that in the future the scientific direction of ARM, specifically as it pertains to the solar short wave radiation budget but generalizing as well to many other ARM program issues, should give first priority to area (1) and second priority to area (2).

Our recommendation for area (1) with respect to the solar, short wave radiation budget issues is that major effort should be concentrated on simultaneous measurement of all atmospheric constituents and processes in a small region. For example, radiation fluxes should be measured as a function of angle and wavelength. The Oklahoma site is well suited for such measurements, but additional instruments and platforms are needed. The measurements directed toward understanding the physics (purpose (1)) will of course also be helpful in providing input to GCM models (purpose (2))

Our recommendation for area (2) is that local measurements should be continued but the style of interpretation should be changed. A GCM should be used to calculate the statistical behavior of any quantity that can be locally observed over time, and the calculated behavior should be directly compared with the observed behavior. This would avoid the confusion introduced by interpreting observations through a filter of poorly-defined global parameters such as "Cloud Forcing" and "Clear-Air Forcing". The GCMs contain a wealth of detailed local statistical information that is ignored in the discussions that we heard.

There is controversy over whether a) there is an anomalous short wave absorption, and if so, whether it is b) due to clouds or c) due to some other component of the atmosphere. We make the following recommendations for further investigation of this question:

1. The instruments should be calibrated to the accuracy needed in order to determine whether the models are indeed in agreement with observations or not. This is difficult when a discrepancy between a model and experiments is on the order of 5%, especially when the desired quantity must be derived from several measurements, all of which have their own errors. For example, the JASONs were informed that although the BSRN and SIROS radiometers agreed amongst themselves, they systematically disagreed with each other, and with Valero's RAMS radiometers located at this site. These discrepancies must be narrowed in order to have confidence in the robustness of the data.

2. The various investigators should use the same models for comparison of their different data sets wherever practical. Because the effect is a discrepancy between a highly paramaterized model output and experimental observations, if the models are varied when the observation conditions are changed it is difficult to assess where discrepancies, if any, lie.

3. The issue of whether the data agree or not with models in clear skies should be resolved by subjecting the radiative transfer code to as rigorous a test as possible under such conditions. Radiation measurements

should be wavelength- and angle-resolved and should be performed under conditions where the aerosol optical depth and optical properties are either well-characterized or are of minimal concern.

4. Clouds should be better characterized during an intensive observational period designed for the purpose of resolving the anomolous absorption controversy. Parameters to be determined should include cloud liquid water content and cloud water droplet size distributions, as well as the vertical distribution of clouds being sampled through the optical path.

5. The data from a dual airplane vertical column measurement experiment such as ARESE should be compared directly to a model for that specific flight path and specific atmospheric and cloud conditions.

6. Measurements at various locations, including those with little or no aerosol content, as are planned for the north slope of Alaska and the tropical western Pacific ARM sites, should be undertaken in an expeditious fashion. Measurements at these sites should challenge the radiative transfer model in as detailed a fashion as that recommended above in point 3) for the Southern Great Plains ARM site.

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