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Principal Investigator: Catherine Gautier
Institute for Computational Earth System Science,
University of California, Santa Barbara

Our most important contribution to the ARM-UAV (Atmospheric Radiation Measurement - Unmanned Aerospace Vehicle) program is our analysis of the aircraft observations taken during the Atmospheric Radiation Measurement Enhanced Shortwave Experiment (ARESE). We analyzed aircraft measurements and compared these to computations made from a 3-D radiative transfer model (SB3D) that was partially developed under the UAV program.

The 3-D radiative transfer model was enhanced and modified to be a research tool for analysis of future UAV missions. The enhancement includes extending the spectral range of the model from 0.25 to 50 μm . Additionally, an ocean surface component has been added to that includes ocean waves, foam, and ocean column microphysics. This component provides a much more accurate characterization of the ocean BDRF for analyzing reflectance measurements over the ocean made by the UAV. A copy of the user manual is attached.

The first part of this analysis was to determine if theoretical calculations of atmospheric column absorption of solar radiation in the presence of clouds matched observations. This analysis included both spectral and broadband fluxes. The second part of the analysis was to analyze the spectral signature of the absorption in order to develop potential physical processes that could explain the discrepancy between observations and models.

Our primary findings for the data analyzed is that broadband solar radiation absorption is underestimated in theoretical models. The difference we found when using the spectral measurements as a guide for our broadband computations is about 20 W m^{-2} . This value is much less than that found by investigators using broadband measurements, but still significant. From the spectral comparison, we identified three potential causes for the discrepancy we found. The most dominant is related to the difficulty of parameterizing aerosols in radiative transfer models. By reducing the single scattering albedo and asymmetry factor of aerosols in our model we were able match the spectral observations in the visible. A second cause is that the silicon detectors used in instruments underestimate the flux near $1.06 \mu\text{m}$ leading to erroneous estimates of atmospheric absorption. Our analysis showed that unresolved O₂-O₂ dimers in this spectral range could not account for the discrepancy. Finally, we demonstrated that cloud droplets required a three-fold increase in cloud albedo to match spectral measurements in the near-infrared region. We modified the droplets by introducing soot in the droplets but showed that the absorption in the visible would be too high for soot to provide the explanation for the cloud absorption anomaly.

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These results have been presented at a number of professional meetings and as an invited talk at the 1998 Gordon Conference on Solar Radiation and Climate. Attached are some recent proceedings and a paper under review in the Journal of Geophysical Research based on this research.

Spectral Signature of Solar Radiation Absorption

Catherine Gautier^{1,2}, William O'Hirok¹ and Paul Ricchiazzi¹
Institute for Computational Earth System Science
University of California Santa Barbara
Santa Barbara, California

Point-of-contact: gautier@icess.ucsb.edu, tel: 805-893-8095

¹ Institute for Computational Earth System Science, University of California Santa Barbara

² Geography Department, University of California, Santa Barbara

Introduction

Many studies have addressed the issue of the absorption of solar radiation within the atmosphere, in both cloud-free and cloudy conditions (e.g., Stephens and Tsay, 1990). Comparisons between modeled solar radiation absorption and observations suggest that the models underestimate the amount of radiation absorbed by the atmosphere for both clear and cloudy skies (Ramanathan et al. 1995, Cess et al., 1995, Pilewskie and Valero, 1995, and Kato et al., 1997).

The Atmospheric Radiation Measurement Enhanced Shortwave Experiment (ARESE) was conducted in the fall of 1995 to address the issue of enhanced absorption in a cloudy atmosphere from an observational perspective. Measurements were obtained above and below clouds, with both spectral and broadband radiometers. No in-cloud observations were, however, collected. An analysis of broadband observations for one day by Zender et al. (1997) for one day suggests a suspiciously large (nearly 100Wm^{-2}) difference between modeled and observed absorption.

In an attempt to elucidate the possible causes for such large absorption, this paper describes the observed spectral characteristics of the absorption for the day analyzed by Zender and compares them with those produced by a model designed to simulate the observations and provide physical insight.

Spectral Observations

Two aircraft, flying above and below clouds, were equipped with identical Radiation Measurement System (RAMS) and a Total Direct Diffused Radiometer (TDDR), measuring solar irradiance at seven spectral bands (approximately 10 nm wide) centered at 0.500, 0.862, 1.064, 1.249, 1.501, 1.651 and 1.750 μm (Valero *et al.*, 1997a). Nadir viewing spectral reflectance (0.418 - 1.096 μm) was also obtained from observations made by the Scanning Spectral Polarimeter (SSP) on the highest aircraft. Only the spectral data are used in this study.

Model Simulations

To evaluate the consistency between the different sets of spectral observations and diagnose the physical processes involved in enhanced absorption, simulated fluxes were computed for a synthesized cloud field. To ensure that the cause of the enhanced absorption was not 3-D effects and to match the spatial variability of the diffused upwelling flux, the 3-D Monte Carlo radiative transfer model described in O'Hirok and Gautier (1998) was used. The variability of the cloud liquid water distribution field was derived from downwelling flux observations obtained from the TDDR at 0.500 μm . The field is presented on Fig. 1. The mean liquid water path is 302 g m^{-2} . The cloud droplet radius distribution has an average r_e of 7.3 μm and follows a modified gamma size distribution. The corresponding mean cloud optical depth, τ is 63. The cloud droplet single scattering albedo, extinction efficiency and phase function were computed directly from Mie theory for each spectral calculation. Pressure, temperature, and water vapor vertical profiles were

derived from soundings at the Cloud and Radiation Testbed (CART) site, while ozone amount was obtained from surface measurements.

Model and Observations Comparisons

Spectral Variations of Albedo and Transmission

Comparisons of model computations with measurements were made (but are not shown here) for the seven spectral channel TDDR at the level of both aircraft and with the SSP. In general, there was very good agreement (better than 5%) with the TDDR downwelling spectral radiation flux and the SSP nadir upwelling spectral flux. Comparisons between upwelling flux for most channels provided fair results for most channels (within 10%), except for 1.06 μm , and a general deterioration for the longer wavelength channels. Comparisons between modeled and SSP observed upwelling flux around 1.06 μm also indicate a significant discrepancy.

To reduce the noise in the instantaneous measurements, they were averaged over the length of the flight. The results from this comparison are presented on Fig. 2a and b for albedo and transmission. On both figures the vertical bars indicate the magnitude of the standard deviation (from the flight average). For albedo, the model results and the SSP observations are in exact agreement at 0.500 μm , suggesting the reasonableness of the model results and the input cloud field. Differences between model results and observations exist for most other TDDR channels. A large discrepancy exists between model computations and SSP observations at 1.06 μm . For transmission, there is a much better agreement between model and observations, except for 1.06 μm .

Spectral Variations of Absorption

The comparisons discussed above suggest that the model provides a reasonable description of the cloud environment that existed on the analyzed day. Therefore, it can be used to interpolate between discrete measurements and to compute the column spectral radiation absorption for that flight. The flight-averaged spectral distribution of atmospheric column absorption has therefore been computed from the model and is compared with values computed from the aircraft observations on Fig. 3. Significant differences exist between the computed and the observed absorptance, reflecting the differences in the albedo and transmission discussed above. In general, the agreement is best for the shorter wavelengths regions (0.500 μm) and deteriorates for longer wavelengths. A large difference exists at 1.06 μm and for the three longest wavelengths of the TDDR (1.501, 1.651 and 1.750 μm).

Enhanced Absorption

The results presented above are indicative of the possible existence of some absorption not represented by the model. Some of this absorption could result from uncertainties in the measurements, but the accuracy noted by the instrument providers is smaller than the unexplained absorption. In an attempt to minimize the difference between modeled and observed absorption, we have modified the input parameters to our model in such a way as to maximize the modeled absorption, while keeping the input data within realistic bounds. Since the absorption results are relatively insensitive to atmospheric parameters such as temperature and water vapor profiles, and ozone amount, we have limited our modifications to the aerosol and cloud droplet properties. The results of these changes are presented in Fig. 4. The best fit between modeled and observed absorption has been obtained by slightly changing the aerosol optical depth (from 0.12 to 0.15), the single scattering albedo from 0.938 to 0.82 and the asymmetry factor from 0.67 to 0.61. For the cloud droplets the co-albedo increased by a factor 3. The agreement between modeled and observed absorption with these tuned parameters is now very good for almost all wavelengths with an exception at 1.06 μm , where the modeled absorption is still much smaller than that observed.

Discussion

The decrease of the aerosol single scattering albedo and asymmetry factor required to reconcile the shorter wavelengths modeled values with the observations suggest a type of aerosol more absorbing than typical urban aerosol. This result is not too surprising in view of other results (Ricchiazzi et al., 1999) that indicate that to match clear sky diffuse irradiance observations with theory requires highly absorbing (soot-like) small particles. In fact, when such small particles are included in the present computations, a better agreement between model and observations is obtained for the spectral distribution of absorption at the shortest wavelengths.

The more puzzling aspect in the closure between observed and modeled absorption is the requirement for very absorbing cloud droplets (co-albedo 3 times that of pure water). This conclusion is entirely based on near infrared measurements of the TDDR. If we exclude purely instrumental problems, the only physically sound explanation that quantitatively matches these results corresponds to a small amount of drizzle in the cloud layer. A sensitivity study indicates that a layer of drizzle of optical thickness 2 is sufficient, and that the effects are only slightly dependent upon the location of that layer. However, the amount of liquid water required for this drizzle is inconsistent with microwave radiometer observations. Soot containing particles were not an acceptable solution since they would produce a spectral signature dramatically different than that observed at the shorter wavelengths.

The other mystery, and the one that may require some modifications to our understanding of the physical processes underlying the observations, is the enhanced absorption at 1.06 μm . This feature is present in both spectral data sets analyzed (TDDR and SSP), which gives us more confidence in its validity. This spectral region corresponds to the absorption by $\text{O}_2\text{-O}_2$ dimers. A modification of the absorption cross-section based on most recent results from Susan Solomon (personal communication) produced too small an absorption value to explain the enhanced absorption derived.

Summary and Conclusion

The results presented here have shown that the spectral signature of absorption in a cloudy layer could be duplicated (except for the 1.06 μm region) with a rather sophisticated radiative transfer model if the absorption by both aerosol and cloud droplets was enhanced. In the case of aerosol, highly absorbing (imaginary part of refractive index between 0.1 and 0.01) small (2 - 5 nm) particles dramatically improved the match between observations and model computations. Duplication of the observed cloud absorption requires a 3-fold increase in cloud-droplet single scattering albedo. The only feature remaining unexplained at this time is the enhanced absorption at 1.06 μm .

These results are only based on one day of observations and therefore they need to be verified. This study suggests the need for additional co-located broadband and spectral observations in clear and cloudy sky conditions in different atmospheric regimes. In-situ aerosol and cloud droplet microphysical measurements will be crucial to unravel the role of these particles in the "enhanced absorption" issue. Finally, accurate absorption measurements are needed at 1.06 μm to understand observed absorption in that spectral region.

References

- Cess, R. D. and co-authors, 1995: Absorption of solar radiation by clouds: Observations versus models. *Science*, 267, 496-499.
- Kato, S., T. P. Ackerman, E. E. Clothiaux, J. H. Mather, and others, 1997 : Uncertainties in modeled and measured clear-sky surface shortwave irradiances, *J. Geophys. Res.*, 102, D22, 25,881-25,898.

O'Hirok, W., and C. Gautier, 1998a: A three-dimensional radiative transfer model to investigate the solar radiation within a cloudy atmosphere. Part I: Spatial effects. *J. Atmos. Sci.*, 55, 2162-2.

Pilewskie, P., and F. P. J. Valero, 1995: Direct observations of excess solar absorption by clouds. *Science*, 267, 1626-1629.

Stephens, G. L. and S.-C. Tsay, 1990: On the cloud absorption anomaly. *Q. J. R. Meteorol. Soc.*, 116, 671-704.

Ramanathan and co-authors, 1995: Warm pool heat budget and shortwave cloud forcing: A missing physics. *Science*, 267, 499-503.

Ricchiazzi, P., C. Gautier, and Y. Shiren, 1999: Spectral and angular characteristics of diffuse solar radiation due to aerosol, ARM Science Team Meeting, San Antonio.

Zender, C. S. and co-authors, 1997: Atmospheric absorption during the Atmospheric Radiation Measurement (ARM) Enhanced Shortwave Experiment (ARESE), *J. Geophys. Res.*, 102, D25, 29901-29915.

Figure Captions

Fig. 1 Synthetic cloud liquid water concentration, effective radius cross-sections and vertically integrated liquid water path.

Fig. 2 Modeled average Egrett flight level spectral albedo and Otter flight level transmission along flight path (gray line). Modeled (plus) and observed (asterisk) albedo average for TDDR channels. SSP (diamond) albedo average and standard deviation.

Fig. 3 Modeled average Egrett-Otter atmospheric column absorptance along flight path (gray line). Modeled (plus) and observed (asterisk) absorptance average for TDDR channels.

Fig. 4. Same as Fig. 3, but for adjusted cloud droplet co-albedo and aerosol.

Fig 1

Fig 2

Egrett - Otter atmospheric column

Fig 3

Fig 4

POTENTIAL PHYSICAL PROCESSES EXPLAINING
THE OBSERVED SPECTRAL SIGNATURE OF
CLOUDY COLUMN SOLAR RADIATION ABSORPTION

Catherine Gautier*, William O'Hirok and Paul Ricchiazzi
Institute for Computational Earth System Science
University of California Santa Barbara

1. INTRODUCTION

Considerable debate has taken place over the last few years concerning the absorption of solar radiation within the atmosphere, in both cloud-free and cloudy conditions (e.g., Stephens and Tsay, 1990). Comparisons between modeled solar radiation absorption and observations suggest that the models underestimate the amount of radiation absorbed by the atmosphere with and without clouds (Ramanathan et al. 1995, Kato et al.). Solving this issue is crucial for climate model predictions, since the amount of solar radiation absorbed by the atmosphere strongly influences the dynamics of both the atmosphere and ocean and the exchanges of heat between the two media.

Gautier et al., 1999 showed that the spectral characteristics of the absorption of solar radiation in an atmosphere containing clouds on October 30, during the 1997 ARESE experiment. The objective of the present paper is to use these observations, together with radiative transfer modeling results, to better understand the physical processes giving rise to the observed spectral absorption.

1. OBSERVATIONS

Two aircraft, flying above and below clouds, were equipped with identical Radiation Measurement System (RAMS) and a Total Direct Diffused Radiometer (TDDR), measuring solar irradiance at seven spectral bands (approximately 10 nm wide) centered at 0.500, 0.862, 1.064, 1.249, 1.501, 1.651 and 1.750 μm (Valero et al., 1997a). Nadir viewing spectral reflectance (0.418 - 1.096 μm) was also obtained from observations made by the Scanning Spectral Polarimeter (SSP) on the highest aircraft. Only the spectral data are used in this study.

2. MODEL

Two models, with 1-D and a 3-D, characteristics, but with the same physics and the same spectral resolution, have been used in this study. First, the 3-D model developed by O'Hirok and Gautier, 1998z) has been run with ARESE observations to evaluate the consistency between the different sets of spectral observations (Gautier et al., 1999). The second, a 1-D radiative transfer model SBDART (Ricchiazzi et al., 1998), has been used to diagnose the physical processes involved in solar radiation absorption. The 3-D model has been used to simulate observed fluxes for a synthesized cloud field that mimics the observed field. The variability of the cloud liquid water distribution field was derived from

downwelling flux observations obtained from the TDDR at 0.500 μm . The field is presented on Fig. 1. . The mean liquid water LWP is 302 g m⁻². The cloud droplet radius distribution has an average r_e of 7.3 μm and follows a modified gamma size distribution. The corresponding mean cloud optical depth, τ , is 63.

Both models used cloud droplet single scattering albedo, extinction efficiency and phase function computed directly from Mie theory. Pressure, temperature, and water vapor vertical profiles were derived from soundings at the CART site while ozone amount was obtained from surface observations.

3. MODEL AND OBSERVATIONS COMPARISONS

4.1 Spectral variations of Absorption

Comparisons of albedo and transmission were presented in Gautier et al., (1999). They showed that the 3-D model was reasonably representative of the radiative environment that existed on 10/30/97. The model was, therefore, used to interpolate between discrete measurements and to compute the flight-averaged spectral column absorption. The results are compared with values computed from the aircraft observations on Fig. 2. Significant differences exist between the computed and the observed absorptance with the better agreement for the shorter wavelengths regions (0.500 and 0.946 μm), and a large difference at 1.06 μm and for the three longest wavelengths of the TDDR (1.5, 1.651 and 1.750 μm).

4.2 Modified Absorption Spectral Variations

The difference between the observations and the model results presented above could be an indication that the model is unable to represent the absorption that is occurring in reality. Some of this absorption could result from uncertainties in the measurements, but the accuracy noted by the instrument providers is smaller than the unexplained absorption. In order to quantitatively determine the properties needed, we have modified the input parameters to our model, in such a way as to minimize the difference between modeled and observed absorption. This resulted in a maximization of the modeled absorption, while keeping the input data within realistic bounds. The results from these changes are presented in Fig. 3. The best fit between modeled and observed absorption has required a slight change in aerosol optical depth (from 0.12 to 0.15), single scattering albedo (from 0.938 to 0.82) and asymmetry factor (from 0.67 to 0.61). For the cloud droplet properties the best fit required a small increase in cloud optical depth (a factor of 1.09) and a large increase in co-albedo by a factor 3.

* Corresponding author address: Catherine Gautier, ICES, Ellison Hall, UCSB, Santa Barbara, CA 93106; email: gautier@ices.ucsb.edu

The agreement between modeled and observed absorption with these tuned parameters is now very good for almost all wavelengths with an exception at 1.06 μm , where the modeled absorption is still much smaller than that observed.

4. PHYSICAL PROCESSES POTENTIALLY ENHANCING ABSORPTION

To investigate the processes that could play a role in enhancing absorption on the day analyzed, our 1-D model has been used. A series of sensitivity studies has been performed for each of the candidate processes discussed below. The reference case (nominal conditions used for the 3-D computations), as well as the TDDR observations, are plotted on each of the graphs presenting the results of the sensitivity studies.

5.1 Aerosol Properties

The low values of aerosol single scattering albedo and asymmetry factor required to reconcile the modeled with the observed values in the short wavelength region suggest a type of aerosol more absorbing than typical rural aerosol. This is in agreement with other indirect results for the CART site in clear sky conditions. Ricchiazzi et al. (1999) had to introduce small, highly absorbing (soot-like) particles in their computations to match clear sky diffuse observed irradiance with that modeled. Using the same aerosol particles, the present computations agree with the observations at the shortest wavelengths, as shown on Fig. 4.

5.2 Cloud Droplet Co-Albedo

To reconcile observed and modeled absorption at longer wavelengths, very absorbing cloud droplets are needed. Their co-albedo must be 3 times that of pure water. Excluding instrumental problems with the TDDR as the reason for this high co-albedo value, we performed sensitivity studies to assess the origin of this absorption, from which we report on two of them.

First, we computed the spectral absorption properties for droplets containing soot in their core. As found by other authors, Fig. 5 shows that soot containing particles are not an acceptable solution for the shorter wavelengths.

A second sensitivity study was performed this time with drizzle (100 μm water particles) in different locations. The results from these studies, presented on Fig. 6, indicate that a layer of drizzle of optical thickness 2 would be sufficient to match the observations. Drizzle layers were observed over parts of the flight (Pat Minnis, personal communication), however the corresponding amount of water seems too large for the cloud layer observed.

5. MISSING PHYSICS

Besides the physics needed to explain the observed cloud co-albedo, the only remaining missing one is that that would explain the observed enhanced absorption at 1.06 μm . Since this feature is present in both spectral data sets analyzed here, we have a certain level of

confidence in its validity. This spectral region corresponds to the absorption by $\text{O}_2\text{-O}_2$ dimers. Recently updated absorption coefficients (Susan Solomon, personal communication) produces too small an absorption value to explain the enhanced absorption derived.

6. SUMMARY AND CONCLUSION

The results presented here have shown that the spectral signature of absorption in a cloudy layer could be duplicated (except for the 1.06 μm region) with a rather sophisticated radiative transfer model, if the absorption by both aerosol and cloud droplets was enhanced. In the case of aerosol, highly absorbing (imaginary part of refractive index between 0.1 and 0.01), small (2 - 5 nm) particles dramatically improved the match between observations and model computations. Duplication of the observed cloud absorption required a thin layer of drizzle (large droplets). The only feature remaining unexplained at this time is the enhanced absorption at 1.06 μm .

These results are only based on one day of observations and need to be verified. This study suggests the need for additional co-located broadband and spectral observations in clear and cloudy sky conditions in different atmospheric regimes. In-situ aerosol and cloud droplet microphysical measurements will be crucial to unravel the role of these particles in the "enhanced absorption" issue. Finally, accurate absorption measurements are needed at 1.06 μm to understand observed absorption in that spectral region.

8. REFERENCES

- Cess R. D. and co-authors, 1995: Absorption of solar radiation by clouds: Observations versus models. *Science*, **267**, 496-499.
- Gautier C., W. O'Hirok and P. Ricchiazzi: Spectral Signature of Solar Radiation Absorption, 1999 ARM Science Team Meeting. San Antonio, TX.
- Kato S. and co-authors 1997 : Uncertainties in modeled and measured clear-sky surface shortwave irradiances, *J. Geophys. Res.*, **102**, D22, 25,881-25,898.
- O'Hirok, W., and C. Gautier, 1998a: A three-dimensional radiative transfer model to investigate the solar radiation within a cloudy atmosphere. Part I: Spatial effects. *J. Atmos. Sci.*, **55**, 2162-2.
- Stephens and Tsay, 1990: On the cloud absorption anomaly. *Quart. J. Roy. Meteor. Soc.*, **106**, 671-704.
- Ricchiazzi et al., 1999: Spectral and angular characteristics of diffuse solar radiation due to aerosol, ARM Science Team Meeting, San Antonio.
- Zender. C. S. and co-authors, 1997: Atmospheric absorption during the Atmospheric Radiation Measurement (ARM) Enhanced Shortwave Experiment (ARESE), *J. Geophys. Res.*, **102**, D25, 29901-29915.

Fig 4. Spectral Variations of Absorption for an aerosol layer composed of small absorbing particles

Fig 5. Spectral Variations of Absorption for cloud droplets with soot-containing core of different radius

Fig 6. Spectral Variations of Absorption for drizzle layer of different optical depth

**Spectral Signature of Column Solar Radiation Absorption
During the Atmospheric Radiation Measurement Enhanced Shortwave
Experiment (ARESE)**

William O'Hirok¹, Catherine Gautier^{1,2}, and Paul Ricchiazzi¹

(1) Institute for Computational Earth System Science and

(2) Department of Geography

University of California Santa Barbara, CA

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Abstract

Spectral and broadband shortwave radiative flux data obtained from the Atmospheric Radiation Measurement Enhanced Shortwave Experiment (ARESE) are compared with 3-D radiative transfer computations for the cloud field of October 30, 1995. Because the absorption of broadband solar radiation in the cloudy atmosphere deduced from observations and modeled differ by 135 Wm^{-2} , we performed a consistency analysis using spectral observations and the model to integrate for wavelengths between the spectral observations. To match spectral measurements, aerosols need a reduction in both single scattering albedo (from 0.938 to 0.82) and asymmetry factor (from 0.67 to 0.61), and cloud droplets require a three-fold increase in co-albedo. Even after modifying the model inputs and microphysics the difference in total broadband absorption is still of the order of 75 Wm^{-2} . Finally, an unexplained absorber centered around $1.06 \mu\text{m}$ appears in the comparison that is much too large to be explained by dimers.

1. Introduction

The absorption of solar radiation in the atmosphere has been a considerably debated issue for more than four decades. For many years, the focus was on understanding and explaining the discrepancy between aircraft observations and theoretical estimates of solar radiation absorption and reflectance by clouds (e.g., Stephens and Tsay, 1990). A new version of the debate was initiated a few years ago following comparisons between satellite observations and climate model computations of the absorption of solar radiation in cloudy skies. Essentially, the contention is that while in climate models the absorption of solar radiation in cloudy and clear atmospheres is equivalent, observations suggest much greater absorption in a cloudy atmospheric column. This discrepancy is a crucial issue for climate model predictions, since the amount of solar radiation absorbed by the atmosphere strongly influences exchanges of heat between atmosphere and ocean and their dynamics.

Following the advent of Earth radiation measurements from space (Ramanathan, 1987), a high degree of confidence now exists on the total solar radiation absorbed by the Earth system (combined atmosphere and surface) for clear or cloudy conditions. However, the determination alone of the solar radiation absorbed by the atmosphere requires the differential measurement of the observed net fluxes between both the top of the atmosphere and surface. This measurement is, itself, fraught with uncertainties. There are two extreme positions from which one can speculate about the discrepancy between observations and models: the difference is produced by observational or analysis uncertainties or the discrepancy is the result of climate model inadequacies. Most likely, the solution lies somewhere in between these two competing explanations.

Over the last few years, many papers have appeared that deal with the topic of excess observed absorption (referenced to model computations), also commonly referred to as anomalous absorption (Ramanathan et al. 1995, Cess et al., 1995, 1996, Pilewskie and Valero, 1995, Waliser et al., 1996 and Collins, 1998). These papers have shown the existence of excess absorption ($15 - 35 \text{ Wm}^{-2}$ diurnal average) that is both too large to be attributed to standard observational error and cannot be explained by existing radiative transfer theory. Their evidence is based on surface or low-flying aircraft observations coupled with top of the atmosphere observations from aircraft or satellites. However, using similar approaches Li and Moreau (1995) and Imre et al. (1996) among others suggest that anomalous absorption is negligible or

at most limited to the Tropics. Although many physical mechanisms have been suggested to explain anomalous absorption (Stephens and Tsay, 1990) none have been clearly able to account for its magnitude for all observed conditions.

In order to decisively answer the claim of anomalous absorption, the Atmospheric Radiation Measurement Enhanced Shortwave Experiment (ARESE) was conducted by the Department of Energy in fall, 1995. ARESE consisted of many different surface, aircraft, and satellite observations. Based on a set of coordinated aircraft observations, recent papers (Zender et al., 1997, Valero et al., 1997a, Valero et al., 1997b) have supported the existence of anomalous absorption in cloudy sky conditions with computed magnitudes of nearly 100Wm^{-2} for the flight of October 30, 1995. This most recent demonstration (Zender et al., 1997) is based on a set of broadband measurements. However, Li et al. (1999) using a variety of observations from more sources including aircraft, spacecraft and ground-based instruments suggest that the anomaly may be related to the “quality” of the total solar broadband radiometer data.

In this study, we check the consistency of the broadband observations with spectral measurements taken during the ARESE experiment to evaluate whether uncertainties in these observations could be the source of the anomaly. Toward that end we employed a 3-D spectrally resolved radiative transfer model developed to simulate the 3-D radiation field in a cloudy atmosphere (O'Hirok and Gautier, 1998a). Although we anticipated minimal 3-D absorptive effects with the type of clouds present on the day analyzed, the 3-D model was used to provide a realistic smooth upwelling radiation field that cannot be directly obtained from standard 1-D models.

Here we present observations and model computations for a 3-D representation of the thick stratus cloud system that occurred during ARESE on October 30 1995 (103095). Consistency amongst different sets of observations is analyzed and discussed, and modifications to physical processes are provided to demonstrate how the gap between the observations and theory can be reduced.

2 Method

2.1 Observations

Radiometric measurements were obtained from the Grob Egrett aircraft flying over the cloud layer at approximately 13 km above ground level (agl) and the Twin Otter aircraft located beneath the cloud at a

mean altitude of 0.5 km agl. Two identical radiometric instrument packages of the Radiation Measurement System (RAMS) were outfitted on each aircraft (Valero et al., 1997b). Two types of broadband radiometric instruments and a spectrally resolved radiometer were deployed, each providing simultaneous observations in both the nadir and zenith direction. The Total Solar Broadband Radiometer (TSBR) encompasses the solar spectrum between 0.224 and 3.91 μm , and the Fractional Solar Broadband Radiometer covers the near-infrared between 0.68 and 3.3 μm . As calculated in Zender et al. (1997), the visible irradiance is defined as the difference between the TSBR and FSBR. The solar irradiance at seven spectral bands (approximately 10 nm wide) centered at 0.500, 0.862, 1.064, 1.249, 1.501, 1.651 and 1.750 μm were measured using the Total Direct Diffused Radiometer (TDDR). The absolute accuracy of the TSBR/FSBR is probably of the order of 2 – 3%, and that of the TDDR is 5 % (Valero et al., 1997b).

The TSBR/FSBR data sets used in this study have a release date of August 12, 1997 for the Egrett and August 22, 1997 for the Twin Otter. The TDDR data sets release dates are June 18, 1997 for the Egrett and June 9, 1997 for the Twin Otter. These data sets represent the latest refined calibration "b1" data sets and are the most currently available as of June 25, 1998 (Bush, 1998 personal communication).

TDDR fluxes used in the analysis of this paper have been converted from Wm^{-2} to $\text{Wm}^{-2}\mu\text{m}^{-1}$ by dividing by the spectral bandwidths contained within the TDDR data files. Additionally, model computations of TSBR and FSBR fluxes use the filter functions supplied with the TSBR/FSBR data sets. Nadir viewing spectral reflectance (0.418 - 1.096 μm) from the Egrett was also obtained from observations made by the Scanning Spectral Polarimeter (SSP). The SSP has a spectral resolution varying between 0.015 to 0.03 μm and has a flux accuracy of approximately 5 % throughout most of its spectral range.

2.2 Model and Model Input

To examine the consistency of the spectral and broadband fluxes observed aboard the Egrett and Twin Otter, simulated fluxes were computed for a synthesized cloud field using a 3-D Monte Carlo based radiative transfer model described in O'Hirok and Gautier (1998a). Two simulations were conducted. The first simulation uses best estimates of the optical properties of the atmosphere occurring at the time as input to the model (i.e. atmospheric gases, aerosols, cloud microphysics, surface albedo). The second simulation is a sensitivity study that uses optical properties adjusted to best match the observed fluxes.

The synthetic cloud field optical thickness is derived from regridding the 0.500 μm downwelling

flux (17:30 - 19:21 UTC) measured aboard the Twin Otter to 400 points and matching the irradiance at each point to plane-parallel cloud radiative transfer computations (Ricchiazzi et al., 1998) for similar cloud and atmospheric conditions. The mean cloud base and cloud top heights are estimated from the cloud detection lidar aboard the Egrett and a micropulse lidar located at the CART central facility. The cloud layer is partitioned vertically into 30 layers, each 40 meters thick. Horizontally, the layers are sectioned into cells of 1 km length over a distance of about 400 km. Cloud top altitude variability is related to the total liquid water path (LWP) of each horizontal column. The vertical distribution of cloud liquid water content varies with the slope of the adiabatic curve but at an amount representing less than 40% of the saturated adiabatic liquid water content. Internal variations of the LWC are based on a multiplicative cascade approach that uses weighting coefficients derived directly from the variability of the LWP (O'Hirok and Gautier, 1998b). Optical properties within each cell are homogeneous. The liquid water content (LWC) of a given cell is related to the extinction coefficient, σ_{ext} , by the expression

$$\sigma_{ext} = (3 Q_{ext} LWC) / (4 \rho r_e) \quad (1)$$

where r_e is the effective radius of the cloud droplet distribution, Q_{ext} is the cloud droplet extinction efficiency, and ρ is the density of water.

Although the radiative fluxes are highly sensitive to r_e , no direct measurements of this quantity are available. In this study, we took what we consider the most conservative approach and bounded r_e to values between 6 and 9 μm . The cloud droplet radius distribution is specified as a modified gamma size distribution. Within these limits, r_e is allowed to vary spatially according to the LWC (in g m^{-3}) at a specific location within the cloud layer and generally follows the relationship

$$r_e = 100 \times [LWC \times 3 / (4\pi \times N)]^{1/3} \quad (2)$$

where N is the droplet number concentration taken as 600 cm^{-3} (Bower et al., 1994). Figure 1 shows cross-sections of LWC and r_e and the vertically integrated LWP for the synthetic cloud. The mean LWP is 316 g

m^{-2} equating to a mean optical thickness, τ , of 66 for an average r_c of $7.3 \mu\text{m}$.

All model computations are performed at $0.005 \mu\text{m}$ spectral intervals from 0.25 to $5.00 \mu\text{m}$ using the three term k -distribution method of LOWTRAN7 (Kneizys et al. 1988). The cloud droplet single scattering albedo, extinction efficiency, and phase function are computed directly from Mie theory for each spectral interval (Wiscombe, 1980). As part of the sensitivity study, a second set of computations was performed and the cloud droplets' co-albedo multiplied by 3 to more closely match the observed absorptance for the TDDR channels at 1.501 , 1.651 and $1.750 \mu\text{m}$.

Model inputs of pressure, temperature, and water vapor vertical profiles are derived from the 17:30 UTC sounding at the CART site. These quantities are interpolated onto the model's 64 layer vertical grid, representing the atmosphere between the surface and 100 km. A standard ozone profile (McClatchey et al., 1972) is employed that has been adjusted to provide a total Dobson unit value (264) midway between those obtained at Boulder, Colorado and Nashville, Tennessee for 950130 (data obtained from the National Oceanic and Atmospheric Administration Climate Monitoring and Diagnostics Lab total ozone archive). For the strongest absorbing wavelengths, the results should be rather insensitive to the ozone profile since the altitude of the simulated fluxes is well below the altitude where the ozone concentration reaches its highest value.

For the surface, a Lambertian vegetation reflectance model is used to parameterize the shape of the spectral albedo (Reeves and Landen, 1975). To accurately portray the actual conditions during ARESE, this spectrum has been adjusted to provide a best fit to the observed TDDR spectral albedo without changing its overall shape. Additionally, the modeled albedo spectrum is constrained so that the broadband albedo is equal to the observed value of 0.17. Since the TDDR upwelling measurements aboard the Twin Otter are unreliable for 951030, the albedo observed from that aircraft for the clear-sky day of 951011 is used. While variations of surface albedo can dramatically alter the flux transmitted to the surface, the net effect on atmospheric absorption is negligible. Hence, errors in estimating the surface albedo should not alter any of the conclusions found in this study.

Aerosol represents a challenge for model input, since radiative fluxes in the visible region of the solar spectrum are highly sensitive to their concentration and microphysics. Although measurements of aerosol optical depth are routinely made for clear skies by directly looking at the sun, sun photometric

techniques cannot be employed for overcast conditions. Hence, the boundary layer aerosol optical depth must be estimated for 951030. Based on observations for clear days preceding 951030, we employ the same optical depth as used by Zender et al. (1997) of 0.12. Likewise, we use the same stratospheric aerosol optical depth of 0.006.

A rural type aerosol (Shettle and Fenn, 1975) represents the aerosol microphysics with the single scattering albedo set at 0.938 and the asymmetry factor specified at 0.67. These are based on climatological values as reported by d'Almeida et al. (1991). For the sensitivity study, the aerosol microphysics are altered so that the computed atmospheric absorptance at 0.500 μm equals the observed absorptance between the Egrett and the Otter. This adjustment represents an increase in aerosol optical depth to 0.17, a reduction in the aerosol single scattering albedo to 0.82, and a lowering of the asymmetry factor to 0.61. By increasing aerosol absorption, the albedo at the Egrett flight level is lowered. To bring the simulated albedo back to the observed for the sensitivity study, the cloud optical thickness is increased by 9%.

2.3 Model computations

Upwelling and downwelling irradiance were computed at all layers but stored for the Egrett flight level, Otter flight level, and surface. For simulating the broadband instruments, the results were spectrally integrated and convolved with the TSBF and FSBF supplied filter functions. An *a-priori* estimate of the photons required for the Monte Carlo computation is difficult to make. This difficulty arises because of the varying spectral nature of gaseous absorption, aerosols, surface albedo and cloud microphysics and the use of photon weights. Generally, for a given wavelength the termination of the Monte Carlo process is based on a convergence criterion as described in O'Hirok and Gautier (1998a). For non-TDDR wavelengths where broadband and spatial integration greatly reduces statistical noise, the Monte Carlo process is completed when the atmospheric absorption between the Egrett and ground, the upwelling irradiance at the Egrett, and the downwelling flux at the ground change by less than 0.5 % for each horizontal cell. For each of the TDDR wavelengths, the percent change was reduced to 0.1% in order to increase the number of photons and the accuracy of the computations. At each of these wavelengths at least 2,400,000 weighted photons were processed. Overall, at least 100 million weighted photons were utilized per cloud field simulation.

3 Results

In this section, we present a comparison between the modeled (using best estimates of atmospheric optical properties) and observed upwelling and downwelling fluxes and atmospheric absorption between the Egrett and Otter flight levels. It should be recalled that the cloud field used in the model computations is derived from the channel 1 ($0.500\ \mu\text{m}$) downwelling flux measured aboard the Otter. Naturally, this condition will bias the fluxes such that better agreement will be found between modeled and observed downwelling fluxes below the cloud than for the upwelling fluxes at the Egrett flight level. However, since the atmospheric absorption is derived as the difference in the net fluxes modeled and observed at the two flight levels, there is no appreciable biases encounter in the computed absorption, and hence, there are no effects on the conclusions found in this study.

3.1 Broadband Upwelling and Downwelling Flux Flight Comparisons

First, we examine two quantities: the upwelling broadband radiation flux for the TSBR and FSBR instruments on the Egrett above the cloud system and the downwelling broadband radiation flux for the TSBR and FSBR instruments on the Otter below the cloud system. The results of our model computations are compared to the observations in Figures 2a and b, where the solid line represent the instantaneous flux and the dashed line the flight average. A large difference appears between the Egrett upwelling observations and model computations for the visible (VIS), near-infrared (NIR), and total broadband (TOTAL) spectral regions. However, for the zenith downwelling flux on the Otter, there is comparatively excellent agreement for the visible and a good agreement for the total but a significantly poorer agreement for the NIR. The excellent agreement with the VIS downwelling flux is to be expected since the cloud optical depth was derived from $0.500\ \mu\text{m}$ TDDR downwelling irradiance measured aboard the Otter. Nonetheless, since the VIS is obtained as the difference between the TOTAL and the NIR, the agreement is not straightforward. This agreement in the VIS region and the disagreements in the two other spectral regions (TOTAL and NIR) suggest that if the two measurements (TOTAL and NIR) are biased, the biases cancel out. Also, proportionally, the bias for the zenith downwelling NIR flux would be larger than that for the TOTAL. Values representing these comparisons are presented in Table 1 (columns 1, 2 and 3).

3.2 TDDR Channels Flight Comparisons

As previously mentioned, in this paper we have modeled the TDDR spectral fluxes. Comparisons with the observations are presented in Figures 3a and b, and the results are quantified in Table 2a and b. For the zenith downwelling spectral flux, there is excellent agreement between the model fluxes and observations for all TDDR channels except channels 3 ($1.064\ \mu\text{m}$) and 5 ($1.501\ \mu\text{m}$). In the case of TDDR channel 5, the difference may be attributed to what seems to be a zero offset problem in the instrument. Since the cloud field was tuned to the Otter observed downwelling flux for channel 1 ($0.500\ \mu\text{m}$) only, it was not fully expected that good agreement should also be found for channels 2, 4 and 6. Additionally, if there is absorption not fully accounted for in the model it is difficult to surmise an absorbing mechanism that would not partially reduce some of the downwelling flux in these channels. However, as noted previously, the downwelling flux below the cloud is highly sensitive to the surface albedo. Because vegetation is highly reflective in the near-infrared, relatively minor variations in the surface albedo estimate may mask reductions in transmittance through the cloud. Still, since absorption is computed from net fluxes and not just transmittance, errors in the estimate of surface albedo will have little impact on the calculation of atmospheric absorptance.

For the nadir upwelling spectral radiation flux at the Egrett (left panels), the results of the comparisons are generally poor for most channels except $0.862\ \mu\text{m}$, and generally deteriorate for the longer wavelength channels. The spatial smoothing of the 3-D computations for the upwelling flux is apparent in the good spatial coherence between the observed and modeled signals. Interestingly, the relationship inverts at the longest wavelengths, for which we cannot offer any explanation.

3.3 Flight-Averaged Albedo and Transmission Comparisons

To examine the consistency of the observed and modeled data, both spectrally and broadband, averages over the length of the flight and over the spectral interval covered by the instrument have been plotted in Figures 4a and b. The top figure (4a) shows the spectral variations of the flight-average modeled (thin line) albedo at the Egrett flight level, with the discrete spectral observations for the TDDR. Three of the SSP wavelengths for the Egrett flight level are also indicated on the figure. The bottom figure (4b) shows the spectral variations of the flight average model (thin line) transmission at the Otter flight level with the discrete spectral observations for the TDDR. On both figures the length of the vertical bars

indicate the magnitude of the standard deviation (from the flight average) of the model and observations during the flight. The broadband VIS, NIR and TOTAL values of albedo and transmission are also plotted next to each figure. As noted previously, the visible broadband is computed as the difference between the TSBR and FSBR for both model results and observations.

For albedo, the model results and the SSP observations are in exact agreement at 0.500 μm , suggesting the reasonableness of the model's computation and input. However, the TDDR's albedo at this wavelength is lower by about 0.05. Interestingly, the difference between the broadband VIS albedo and the model is much greater at 0.20. At 0.862 μm the SSP observed albedo falls between the modeled and the TDDR albedo. Further into the near-infrared, the difference for some of the spectral channels approaches 0.2 between the model and the TDDR and 0.12 for the broadband NIR. The largest discrepancy exists between the model computation and both the SSP and TDDR observed albedo at 1.064 μm . Overall, the broadband TOTAL observed albedo is .17 lower than the model results.

For transmission, with exception to the TDDR channel at 1.064 μm , there is excellent agreement (< .01) between the model results and observations. The observed transmission, lower by .03 for this channel, coincides with the large discrepancy in albedo, suggesting either a systematic instrument problem or a deficiency in model physics. The difference is even greater for the broadband NIR, where the observed transmission is .05 lower than the modeled.

3.4 SSP Spectral Comparisons

While the TDDR is limited to a single channel in the visible, the SSP on the Egrett provides continuous spectral data from 0.40 to 1.10 μm . Model computations of nadir upwelling spectral flux are compared to SSP observations of the same parameter in Figure 5 and presented in the form of band computations using a rectangular filter function in Table 3. General agreement exists between the SSP observations and the model computations at the 5% level. The largest differences occur near 0.76 μm and wavelengths further out in the near-infrared at 1.00 μm and higher. The first discrepancy is likely caused by the wide bandwidth of the SSP smoothing the strong molecular oxygen absorption feature at 0.76 μm . The latter, however, coincides with the albedo and transmission discrepancies found previously at 1.064 μm . For the SSP, part of the discrepancy above 1.00 μm may be related to the extreme sensitivity of typical silicon detectors to the temperature of the detector.

As previously noted, the SSP and model results match extremely well at 0.500 μm , and the difference between the model and TDDR albedo at this wavelength is less than .05. When integrated over the wavelengths from 0.42 and 0.68 μm the difference in albedo is less than .01 for the SSP and model, but it approaches .20 for the comparison between the broadband instruments and model computations. Thus, at least within the visible spectrum, the TDDR tends to be more consistent with the SSP and model results than with the broadband instruments. This result is consistent with the findings of Li et al. (1999).

3.6 Absorption Computations

Together, the comparisons presented above suggest that the model is fairly representative of the radiative environment that existed on 103095, and therefore it is reasonable to use it: 1) to interpolate between discrete measurements and 2) to compute the column spectral and broadband radiation absorption for that flight. Atmospheric absorption between the Egrett and Otter is computed by taking the difference between the net fluxes at the two flight levels. Since the upwelling flux measurements aboard the Twin Otter are unreliable for 951030, the upwelling flux at the Twin Otter level is computed by multiplying the Twin Otter level downwelling flux by the surface albedo. This method is used for both the observations and model computations to reduce any biases that may occur by neglecting the intervening atmosphere between the Twin Otter and the ground. In Figure 6, we show the modeled absorptance spectral variations of the flight-averaged atmospheric column (thin line) and compare these values with absorptance computed from the aircraft observations. The broadband results are shown to the right of the spectral plot. Again, the visible broadband is computed as the difference between the TOTAL and NIR broadband.

Significant differences exist between the computed and the observed absorptance, reflecting the differences in the albedo and transmission radiation discussed above. In general, the agreement is best for the shorter wavelengths regions (0.500 and 0.862 μm) and deteriorates for longer wavelengths. A large difference exists at 1.064 μm and at the two longest wavelength TDDR channels (1.651 and 1.750 μm). The differences between the broadband results are very large, about 135 Wm^{-2} for the total broadband. The overall broadband differences are presented in Table 1.

4 Enhanced Absorption Analysis

Temporarily ignoring the Egrett broadband measurements, the multiple data sets analyzed are still indicative of the possible existence of some degree of unexplained or "anomalous" absorption. The questions are then: 1) what is the magnitude of this unexplained absorption, and 2) what are the potential sources of this absorption. To address these questions we have attempted to modify the different input parameters to our model. This modification was made in such a way as to maximize the modeled absorption and reconcile the model results with the observations while keeping the input data within realistic bounds.

First we assume that it is reasonable, in a first evaluation, to exclude the cloud field representation as a source of uncertainty. This assumption is based on the general agreement between observations and model computations in the visible portion of the spectrum. (Note this assumption would not be valid if there exists an unaccounted for, spectrally flat absorber) Accordingly, the following input parameters can be modified in order to improve comparisons: 1) the atmospheric profiles of water vapor and ozone, 2) the surface albedo, and 3) aerosol and cloud droplet properties. A sensitivity study can easily show that unrealistic changes in water vapor and ozone amount would be necessary to reconcile model computations and observations. Although surface albedo changes can strongly modify the transmission to the surface under a cloudy sky, their effect on overall absorption is very small and, henceforth, ignored. On the other hand, changes in aerosol and cloud droplet properties can be altered in such a way as to definitely improve the comparisons.

The results of these modifications are presented in Figure 7. Changes in aerosol properties were made as described in section 2.2, whereas changes in cloud droplet properties were included in terms of a small increase in cloud optical depth (a factor of 1.09) and an increased in co-albedo by a factor of three. The increase in co-albedo forces higher absorption by cloud droplets without specifying the process that induces such an increase. As shown in Figure 7, the agreement with these tuned parameters is excellent for most of the TDDR channels. There remains some minor overestimation of absorption at 1.249 and 1.501 μm . However, those differences are small compared to the large discrepancy remaining at 1.064 μm , where the absorption by the model is still much smaller than that observed.

The right hand area of Figure 7 presents a comparison between broadband (VIS, NIR and TOTAL)

computations and observations. Despite the significant changes in aerosol and cloud microphysical properties, this comparison still indicates a large disagreement between model computations and observations. The total difference has been reduced to about 97 Wm^{-2} . This reduced discrepancy is still inconsistent, however, with the relative agreement now obtained with the spectral observations.

If we analyze in detail the amount of enhanced absorption that each of the changes produce, we find that the aerosol changes induced about 20 Wm^{-2} , and the co-albedo increase resulted in about the same amount, or 20 Wm^{-2} . Still, a discrepancy at (and likely around) $1.064 \mu\text{m}$ exists in both the TDDR and the SSP data. We now attempt to evaluate the maximum potential contribution to the broadband absorption of this unexplained absorption in that spectral region. We use the data to guide us, while making a number of assumptions. The SSP suggests that the absorption anomaly has a broad feature. We can maximize this feature's contribution by assuming that: 1) its spectral extent is from 0.96 to $1.2 \mu\text{m}$ (overlapping with the water vapor absorption) and 2) there is as much absorption observed in transmission as there is observed in albedo by the SSP. Centered about this feature at $1.064 \mu\text{m}$, the net effect is an additional $20 - 25 \text{ Wm}^{-2}$ enhanced absorption.

Considering the relatively good agreement between the model and the spectral observations after adjustment of the input parameters and the maximization of absorption centered around $1.064 \mu\text{m}$, there still remains a discrepancy of about $75 - 80 \text{ Wm}^{-2}$ for the broadband absorption. These results suggest that either large absorption features exist between the spectral channels of the TDDR and are not accounted for in our model, or the spectral measurements are problematic, or the Egrett upwelling broadband data (TSBR and FSBR) are in error. Considering the extreme care and thoroughness that have been applied to the radiometric, angular and spectral calibration of these instruments, it is difficult to speculate on the source of that error.

5 Discussion

One of the main controversies surrounding the anomalous absorption topic, besides its very existence, is whether its magnitude requires the introduction of new physics into climate models. Our results have shown that even if we treat the broadband measurements as problematic, several puzzling questions still remain. The first concerns interstitial aerosols. The values for the single scattering albedo

(0.82) and the asymmetry factor (0.61) that are required to match the observations are much lower than those expected for typical rural aerosols. They are not totally unrealistic, however, if one considers the possibility of large aerosol particles, which have a strong forward scattering coefficient and large absorption properties. Also, these results are consistent with those obtained in clear sky conditions for which the reconciliation of diffuse component observations and model computations require similar changes in aerosol microphysics (Kato et al., 1997, Ricchiazzi et al., 1999).

Next, a cloud water droplet co-albedo of 3 times that predicted by Mie scattering for pure water droplets is required to bring model calculations in line with observations. This result is in keeping with that found by other investigators analyzing cloud reflectance spectra (Twomey and Cocks, 1982; Stephens and Platt, 1987). The presence of absorbing material such as soot inside the water droplets can dramatically increase the co-albedo of a cloud droplet (Chýlek et al., 1984). Using a Mie scattering code (Wiscombe, 1980) we determined that a cloud droplet containing a soot particle of $0.5\ \mu\text{m}$ at its core raises the co-albedo by approximately a factor of 3 for the TDDR channels of 1.501 , 1.651 and $1.750\ \mu\text{m}$. For an estimate of the radiative effects of this cloud droplet for a cloud similar to the 103095 case we used a plane-parallel based radiative transfer model (SBDART, Ricchiazzi et al., 1998). As shown in Table 4, the new computed absorptance values for the TDDR channels of 1.501 , 1.651 and $1.750\ \mu\text{m}$ are close to observed. However, at the shorter wavelengths the absorptance is unrealistically high, with values many times those observed. From these computations it is clear that the inclusion of a soot core within a cloud droplet does not offer a satisfactory explanation to the absorption anomaly.

Equally intriguing as the co-albedo problem is the unexplained absorption at $1.064\ \mu\text{m}$. Although this spectral region is basically devoid of major absorbers (except water vapor at $1.1\ \mu\text{m}$), it does contain $\text{O}_2\text{-O}_2$ dimers. While the reported absorption cross-section of these dimers is not large enough to explain such a large absorption, it is possible that unknown dimer-related processes are at work. To investigate this issue we have included the most recent absorption cross-section as reported by Solomon (personal communication) in SBDART. With this new cross section the optical depth is of the order of 0.015. The result is an increase in cloudy column absorption of only $0.49\ \text{Wm}^{-2}$. Clearly, the effects of adding the new $\text{O}_2\text{-O}_2$ cross section are not sufficient to explain the discrepancy between model computations and observations by both the SSP and the TDDR.

6. Conclusions

We have presented comparisons between modeled and observed radiative flux in the broadband and spectral domains, and we have shown that a significant discrepancy exists between modeled and observed broadband fluxes. This difference is much greater than that expected from the reported uncertainties attributed to either radiometric and angular calibration of the instruments or the uncertainty in model input. We performed a consistency analysis using the spectral observations and the model to integrate for wavelengths between the spectral observations. Even after modifying the model inputs and microphysics and maximizing the absorption in the vicinity of $1.06\text{ }\mu\text{m}$, the difference in total broadband absorption is still of the order of 75 Wm^{-2} . These results show that either there exist large undefined absorbers in the wavelengths between the TDDR channels, or more likely, the broadband observations are problematic as suggested by Li et al. (1999).

Nevertheless, focusing on the spectral observations alone, our analysis suggests that there is some unexplained absorption in the cloudy atmosphere of day 951030 over the CART site in Oklahoma. Both the aerosol and cloud microphysical absorption properties need to be enhanced to reproduce the observations. One could speculate that both aerosols and cloud properties are loaded with soot containing particles that absorb in an unusual manner, but preliminary radiative transfer computations suggest that the spectral signature of absorption for water droplets containing soot cores would be quite different from that observed. A puzzle perhaps more difficult to reconcile is that no known effect can be included in the model simulations to increase absorption to the values observed by both the TDDR and the SSP in the vicinity of $1.064\text{ }\mu\text{m}$.

This study suggests the need for additional co-located broadband and spectral observations in clear and cloudy sky conditions over different regions of the world. In-situ aerosol and cloud droplet microphysical measurements would be important to unravel the role of these particles in the "anomalous absorption" topic. The need for such research efforts is not new. It has been almost two decades since Twomey and Cocks (1982) reported that to match observed cloud reflectance with theory in the near-infrared the co-albedo of cloud droplets needed to be increased by a factor of three- to five, an enhancement not far from that found in this study.

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References

- Bower, K. N., T. W. Choullarton, J. Latham, J. Nelson, M. B. Baker, and J. Jensen, A parameterization of warm clouds for use in atmospheric general circulation models. *J. Atmos. Sci.*, 51, 2722-2732, 1994.
- Cess, R. D. and co-authors, Absorption of solar radiation by clouds: Observations versus models, *Science*, 267, 496-499, 1995.
- Cess, R. D., M. H. Zhang, Y. Zhou, X. Jing, and V. Dvortsov, Absorption of solar radiation by clouds: Interpretations of satellite, surface and aircraft measurements, *J. Geophys. Res.*, 101, 23299-23309, 1996
- Chýlek, P. V. Ramaswamy and R. J. Cheng, Effect of graphitic carbon on the cloud albedo of clouds, *J. Atmos. Sci.*, 41, 3076-3084, 1984.
- Collins, W. D., A global signature of enhanced shortwave absorption by clouds, *J. Geophys. Res.*, 103, 31,669-31,679, 1998.
- D'Almeida, G. A., P. Koepke and E. P. Shettle, Atmospheric aerosols: Global climatology and radiative characteristics, A. Deepak, Hampton, Va., 561 pp., 1991.
- Imre, D. G., E. H. Abramson, and P. H. Daum, Quantifying cloud-induced shortwave absorption: An examination of uncertainties and of recent arguments for large excess absorption, *J. Appl. Meteor.*, 35, 1991-2010, 1996.
- Kato, S., T. P. Ackerman, E. E. Clothiaux, J. H. Mather, and others, Uncertainties in modeled and measured clear-sky surface shortwave irradiances, *J. Geophys. Res.*, 102, 25881-25898, 1997.

Kneizys, F. X., E. P. Shettle, L. W. Abreeu, J. H. Chetwind, G. P. Anderson, W. O. Allery, J. E. A. Selby, and S. A. Clough, AFGL-TR-88-0177, Phillips Lab., Hanscom AFB, MA, 137 pp. [NTIS 206733], 1988

Li, Z., and L. Moreau, Alteration of atmospheric solar radiation by clouds: Simulation and observation, *J. Appl. Meteorol.*, *35*, 653-670, 1996.

Li, Z., A. P. Trishchenko, H. W. Barker, G. L. Stephens, and P. Partain, Analyses of Atmospheric Radiation Measurement (ARM) program's Enhanced Shortwave Experiment (ARESE) multiple data sets for studying cloud absorption, *J. Geophys. Res.*, *104*, 19,127-19134, 1999.

McClatchey, R. A., R.W. Fenn, J. E.A. Selby, F.E.Volz, and J. S. Garing, Optical properties of the atmosphere, *Tech Rep. Environ. Res. Pap.*, *411*, Air Force Cambridge Res. Lab., Bedford, Mass., 1972.

O'Hirok, W., and C. Gautier, A three-dimensional radiative transfer model to investigate the solar radiation within a cloudy atmosphere. Part I: Spatial effects. *J. Atmos. Sci.*, *55*, 2162-2179, 1998a.

O'Hirok, W., and C. Gautier, Comparison of GCM column shortwave radiative fluxes with three-dimensional simulated observations, *Proceedings of the Eighth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, pp. 541-544, United States Department of Energy, Washington D. C., 1998b

Pilewskie, P., and F. P. J. Valero, Direct observations of excess solar absorption by clouds, *Science*, *267*, 1626-1629, 1995.

Ramanathan, V., The role of earth radiation budget studies in climate and general circulation research, *J.*

Geophys. Res., 92, 4075-4095, 1987.

Ramanathan, V., B. Subasilar, G. Zhang, W. Conant, R. Cess, J. Kiehl, H. Grassl, and L. Shi, Warm pool heat budget and shortwave cloud forcing: A missing physics. *Science*, 267, 499-503, 1995.

Reeves, R.G., A. Anson, and D. Landen, Eds., Manual of remote sensing, American Society of Photogrammetry, 1st ed. Falls Church, Va., 1975.

Ricchiazzi, P., S. Yang, C. Gautier, and D. Sowle, SBDART: A research and teaching tool for plane-parallel radiative transfer in the Earth's atmosphere, *Bull. Am. Meteorol. Soc.*, 79, 2101-2114, 1998.

Ricchiazzi, P., C. Gautier, and T. Tooman, Aerosol properties from surface radiation observations, in *Proceedings of the ninth Atmospheric Radiation Measurement (ARM) Science Team Meeting*, in press, United States Department of Energy, Washington D. C., 1999

Shettle, E. P., and R. W. Fenn, Model of the atmospheric aerosols and their optical properties, in *AGARD conference proceedings no. 183*, pp. 2.1-2.16, AGARD, Neuilly sur Seine, France, 1975.

Stephens, G. L., and S.-C. Tsay, On the cloud absorption anomaly, *Q. J. R. Meteorol. Soc.*, 116, 671-704, 1990.

Stephens, G. L. and C. M. R. Platt, Aircraft observations of the radiative and microphysical properties of stratocumulus and cloud fields, *J. Climate Appl. Meteor.*, 26, 1243-1269, 1987.

Twomey, S. and T. Cocks, Spectral Reflectance of clouds in the near-infrared: Comparisons of measurements and calculations, *J. Meteor. Soc. Japan*, 60, 583-592, 1982

- Valero, F. P. J., R. D. Cess, M. Zhang, S. K. Pope, A. Bucholtz, B. Bush and J. Vitko Jr., Absorption of solar radiation by the cloudy atmosphere: Interpretations or collocated aircraft measurements, *J. Geophys. Res.*, *102*, 29917-29927, 1997a.
- Valero, F. P. J., A. Bucholtz, B. Bush, S. K. Pope, W. D. Collins, P. Flatau, A. Strawa and W. J. Y. Gore, Atmospheric radiation Measurements Enhanced Shortwave Experiment (ARESE): Experimental and data details, *J. Geophys. Res.*, *102*, 29929-29937, 1997b.
- Waliser, D. E., W. D. Collins, and S. P. Anderson, An estimate of the surface shortwave cloud forcing over the western Pacific during TOGA COARE, *Geophys. Res. Lett.*, *23*, 519-522, 1996.
- Wiscombe, W. J., Improved Mie scattering algorithms, *Appl. Opt.*, *19*, 1505-1509, 1980.
- Zender, C. S., B. Bush, S. Pope, A. Bucholtz, W. D. Collins, J. T. Kiehl, F. P. Valero and J. Vitko Jr, Atmospheric absorption during the Atmospheric Radiation Measurement (ARM) Enhanced Shortwave Experiment (ARESE), *J. Geophys. Res.*, *102*, 29901-29915, 1997.

Figure Captions

Fig. 1(a) Synthetic cloud liquid water concentration (1b) and effective radius cross-sections. (1c) Synthetic cloud vertically integrated liquid water path.

Fig. 2(a) Egrett flight level observed (dark) and modeled (light) broadband visible, near-infrared and total upwelling solar irradiance. 2(b) Same as Figure 2a but for Otter flight level downwelling solar irradiance. Dashed lines represent mean values for observed and modeled fluxes averaged over the 400 km flight path.

Fig. 3(a) Egrett flight level observed (dark) and modeled (light) TDDR channels of 0.500, 0.862, 1.064, 1.249, 1.501, 1.651 and 1.750 μm upwelling solar irradiance. 3(b) Same as Figure 3a but for Otter flight level downwelling solar irradiance. Dashed lines represent mean values for observed and modeled fluxes averaged over the 400 km flight path.

Fig. 4(a) Egrett flight level modeled spectral albedo average along flight path (gray line). Modeled (+) and observed (*) albedo average and standard deviation of flight path at TDDR channels of 0.500, 0.862, 1.064, 1.249, 1.501, 1.651 and 1.750 μm . (diamond) SSP albedo average and standard deviation of flight path at TDDR channels of 0.500, 0.862 and 1.064. 4(b) Egrett flight level observed (dark) and modeled (light) broadband visible, near-infrared and total albedo. 4(c) Same as Figure 4a, but for Otter flight level transmission and without SSP measurements. 4(d) Same as Figure 4b, but for Otter flight level transmission.

Fig. 5 Average spectral upwelling solar irradiance at Egrett flight level for SSP (dark) and model (light). The modeled flux has been smooth by a 25 nm moving average to better match the effects of the SSP bandwidth.

Fig. 6(a) Modeled average spectral atmospheric absorptance between Egrett and Otter (gray line). Modeled (+) and observed (*) average and standard deviation atmospheric absorptance between Egrett and Otter along flight path at TDDR channels of 0.500, 0.862, 1.064, 1.249, 1.501, 1.651 and 1.750 μm . 6(b) Egrett flight level observed (dark) and modeled (light) broadband visible, near-infrared and total absorptance between Egrett and Otter.

Fig. 7(a) Same as Figure 6a, but for adjusted cloud droplet co-albedo and aerosol. 7(b) Same as Figure 6b, but for adjusted cloud droplet co-albedo and aerosol.

Table Legends

Table 1 Broadband visible, broadband near-infrared and broadband total Egrett nadir, Otter zenith and absorbed solar radiation between aircraft. Values are for observed, modeled (1), observed – modeled (1), adjusted co-albedo and aerosol modeled (2), observed – modeled (2). Modeled (2) values represent the adjustment in aerosol and cloud droplet optical properties.

Table 2 TDDR channels (a) Egrett nadir and (b) Otter zenith fluxes. Values are for observed, modeled (1), observed – modeled (1), adjusted co-albedo and aerosol modeled (2), observed – modeled (2).

Table 3 SSP integrated upwelling irradiance. Values are for observed, modeled (1), observed – modeled (1), adjusted co-albedo and aerosol modeled (2), observed – modeled (2).

Table 4 TTDR channels atmospheric absorptance. Values are for observed, modeled pure water droplet, water droplet co-albedo x 3, and water droplet with 0.5 μm soot core. Model results are based on SBDART computations.

Table 1

	observed Wm⁻²	modeled 1 Wm⁻²	differ. 1 Wm⁻²	modeled 2 Wm⁻²	differ. 2 Wm⁻²
BB VIS					
Egrett Nadir	214.0	317.6	-103.6	307.0	-93.0
Otter Zenith	55.3	53.8	1.5	50.7	4.6
Absorbed	79.7	13.0	66.7	26.4	53.2
BB NIR					
Egrett Nadir	234.7	282.8	-48.1	260.6	-25.9
Otter Zenith	25.1	45.3	-20.2	38.8	-13.7
Absorbed	220.0	149.2	70.8	175.8	44.2
BB TOTAL					
Egrett Nadir	448.7	600.4	-151.7	567.7	-118.9
Otter Zenith	81.4	99.1	-17.7	89.5	-8.1
Absorbed	299.7	162.2	137.5	202.2	97.4

Table 1 Broadband visible, broadband near-infrared and broadband total Egrett nadir, Otter zenith and absorbed solar radiation between aircraft. Values are for observed, modeled (1), observed – modeled (1), adjusted co-albedo and aerosol modeled (2), observed – modeled (2). Modeled (2) values represent the adjustment in aerosol and cloud droplet optical properties

Table 2a

Egrett Nadir Up	observed $\text{Wm}^{-2}\mu\text{m}^{-1}$	modeled 1 $\text{Wm}^{-2}\mu\text{m}^{-1}$	differ. 1 $\text{Wm}^{-2}\mu\text{m}^{-1}$	modeled 2 $\text{Wm}^{-2}\mu\text{m}^{-1}$	differ. 2 $\text{Wm}^{-2}\mu\text{m}^{-1}$
TDDR Ch 1 (0.500)	970.6	1056.7	-86.1	1022.3	-51.7
TDDR Ch 2 (0.862)	506.7	539.8	-33.1	526.2	-19.5
TDDR Ch 3 (1.064)	292.6	353.2	-60.6	340.6	-48.0
TDDR Ch 4 (1.249)	219.0	234.6	-15.6	210.2	8.8
TDDR Ch 5 (1.501)	49.8	74.6	-24.8	47.6	2.2
TDDR Ch 6 (1.651)	76.4	99.0	-22.6	77.1	-0.7
TDDR Ch 7 (1.750)	55.9	68.7	-12.8	52.2	3.7

Table 2b

Otter Zenith Down	observed $\text{Wm}^{-2}\mu\text{m}^{-1}$	modeled 1 $\text{Wm}^{-2}\mu\text{m}^{-1}$	differ. 1 $\text{Wm}^{-2}\mu\text{m}^{-1}$	modeled 2 $\text{Wm}^{-2}\mu\text{m}^{-1}$	differ. 2 $\text{Wm}^{-2}\mu\text{m}^{-1}$
TDDR Ch 1 (0.500)	178.7	185.2	-6.5	174.4	4.3
TDDR Ch 2 (0.862)	104.0	104.0	0.0	96.9	7.1
TDDR Ch 3 (1.064)	61.4	69.4	-8.0	61.2	0.2
TDDR Ch 4 (1.249)	36.6	36.8	-0.2	25.0	11.6
TDDR Ch 5 (1.501)	4.5	3.5	1.0	1.0	3.5
TDDR Ch 6 (1.651)	8.5	8.4	0.1	3.8	4.7
TDDR Ch 7 (1.750)	4.9	5.0	-0.1	2.1	2.8

Table 2 TDDR channels (a) Egrett nadir and (b) Otter zenith fluxes. Values are for observed, modeled (1), observed – modeled (1), adjusted co-albedo and aerosol modeled (2), observed – modeled (2).

Table 3

SSP	observed Wm-2	modeled 1 Wm-2	differ. 1 Wm-2	modeled 2 Wm-2	differ. 2 Wm-2
Band 1 (0.420 – 0.680 μm)	249.1	252.0	-2.9	241.8	7.3
Band 2 (0.685 – 0.940 μm)	135.0	141	-6.0	136.6	-1.6
Band 3 (0.945 – 1.100 μm)	40.7	53.0	-12.3	50.5	-9.9
Total	424.8	445.9	-21.2	428.9	-4.2

Table 3 SSP integrated upwelling irradiance. Values are for observed, modeled (1), observed – modeled (1), adjusted co-albedo and aerosol modeled (2), observed – modeled (2).

Table 4

Absorptance	observed	pure water	co-albedo x 3	0.5 μm soot core
TDDR Ch 1 (0.500)	0.039	0.013	0.013	0.350
TDDR Ch 2 (0.862)	0.053	0.013	0.024	0.370
TDDR Ch 3 (1.064)	0.217	0.063	0.093	0.388
TDDR Ch 4 (1.249)	0.170	0.156	0.252	0.413
TDDR Ch 5 (1.501)	0.705	0.572	0.730	0.634
TDDR Ch 6 (1.651)	0.445	0.310	0.480	0.450
TDDR Ch 7 (1.750)	0.534	0.404	0.558	0.520

Table 4 TTDR channels atmospheric absorptance. Values are for observed, modeled pure water droplet, water droplet co-albedo x 3, and water droplet with 0.5 μm soot core. Model results are based on SBDART computations.

Fig. 1(a) Synthetic cloud liquid water concentration (1b) and effective radius cross-sections. (1c) Synthetic cloud vertically integrated liquid water path.

Fig. 2(a) Egrett flight level observed (dark) and modeled (light) broadband visible, near-infrared and total upwelling solar irradiance. 2(b) Same as Figure 2a but for Otter flight level downwelling solar irradiance. Dashed lines represent mean values for observed and modeled fluxes averaged over the 400 km flight path.

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Fig. 5 Average spectral upwelling solar irradiance at Egrett flight level for SSP (dark) and model (light). The modeled flux has been smooth by a 25 nm moving average to better match the effects of the SSP bandwidth.

Fig. 6(a) Modeled average spectral atmospheric absorbance between Egrett and Otter (gray line). Modeled (+) and observed (*) average and standard deviation atmospheric absorbance between Egrett and Otter along flight path at TDDR channels of 0.500, 0.862, 1.064, 1.249, 1.501, 1.651 and 1.750 μm . 6(b) Egrett flight level observed (dark) and modeled (light) broadband visible, near-infrared and total absorbance between Egrett and Otter.

Fig. 7(a) Same as Figure 6a, but for adjusted cloud droplet co-albedo and aerosol. 7(b) Same as Figure 6b, but for adjusted cloud droplet co-albedo and aerosol.

SB3D USER MANUAL

Santa Barbara 3D Radiative Transfer Model

William O'Hirok (bill@icess.ucsb.edu)

01/99

Earth-Space Research Group

Institute for Computational Earth System Science

Table of Contents

Introduction.....	3
Overview	3
SB3D files.....	7
input. <i>root</i> input.....	9
control. <i>root</i> file.....	15
Output files.....	19
Compiling SB3D	22
Running SB3D.....	23
Model notes.....	25

CAVEAT EMPTOR:

Almost any program of at least moderate complexity will contain some flaws. In most cases after a program has been tested through most of its configurations, it could be stated that the chance of encountering a flaw is “one in a million.” Those odds are fine for most programs. However by the very nature of a stochastic based code, such as SB3D, the program is almost virtually guaranteed to encounter an existing bug even if the odds are more like “one in a billion”. Hence, do not be surprised if at some time the program crashes by hitting one of those “impossible” bugs. Hopefully, most systematic errors have been found and eliminated. But, to sum up NOTHING is guaranteed!

INTRODUCTION

SB3D is a three-dimensional atmospheric and oceanic radiative transfer model for the solar spectrum. The microphysics employed in the model are the same as used in the model SBDART. It is assumed that the user of SB3D is familiar with SBDART and IDL. SB3D differs from SBDART in that computations are conducted on media in three-dimensions rather than a single column (i.e. plane-parallel), and a stochastic method (Monte Carlo) is employed instead of a numerical approach (Discrete Ordinates) for estimating a solution to the radiative transfer equation. Because of these two differences between SB3D and SBDART, the input and running of SB3D is more unwieldy and requires compromises between model performance and computational expense. Hence, there is no one correct method for running the model and the user must develop a sense to the proper input and configuration of the model.

As shown below, there are generally three methods for computing the solar flux for an atmosphere containing clouds. The plane parallel method (PPM) as employed in climate models (e.g. GCMs) and SBDART computes radiation assuming there is no horizontal variability in the atmospheric column. For instance, the flux for a partly cloudy scene would be computed by deriving a mean cloud field, computing the flux for a plane-parallel cloud in an atmospheric column and computing the flux for the same column devoid of any cloud. The fluxes are weighted according to their horizontal coverage and combined to provide the total flux for the scene. The independent pixel approximation (IPM) also assumes plane-parallel clouds, but instead of performing the computation on a mean cloud field the cloud field is partitioned into many atmospheric columns. The flux is computed separately for each column and the results combined to provide a total domain average flux. For both the PPM and IPM, a photon can experience variations in optical thickness and atmospheric constituents microphysics in only the vertical direction. The three-

dimensional (3DM) method differs from the PPM and IPM by allowing photons to traverse horizontally. Hence, photons can encounter variations in optical depth and constituent microphysics in both the vertical and horizontal direction as done in nature. However, spatially the 3DM differs from nature, in that the model domain still has horizontal boundaries, and within the domain the atmosphere is discretized. To account for the horizontal boundary problem, photons exiting a model boundary returns at the opposing boundary with the same trajectory.

The Monte Carlo method is very simple in theory but can be difficult to employ when the media being investigated is multidimensional both in space and substance. Shown below is a diagram of the Monte Carlo method used in SB3D along with the governing equations.

Simply, a weighted photon (can be thought as a packet of photons) enters the model domain, travels a specified distance depending on the extinction coefficient, interacts with an atmospheric constituent (cloud, aerosol or gas), is dewighted by the single-scattering albedo of the constituent, and scattered along a trajectory defined by the phase function. This process is repeated until the photon exits the model domain or the weight of the photon is reduced to below a predefined threshold. Many more photons are needed until the model output converges to a solution within a certain tolerance (see convergence plot below). The total number of photons required depends on the spatial resolution of the desired solution (domain averages vs. column fluxes), the angular resolution (irradiance vs. radiance), the domain complexity (spatial resolution of the model domain), spectral resolution (number of wavelengths), wavelength and desired accuracy.

The time it takes to arrive at a solution is directly related to the number of photons processed and thus the factors mentioned above. While it may only take a matter of minutes to complete a run using SBDART, a run with SB3D can take anywhere from minutes to days to weeks. Along with time considerations, one must also be aware of memory requirements. Shown here is a representation of the model structure.

The model domain is referred to as the shell in the model code. The shell can be of any length, width or height. The shell is partitioned into what are called cells. Each cell represents an atmospheric volume which is completely homogeneous. Variability within the model is based on the distribution of these cells within the shell. Cells can also be of any length, width or height. The number of cells in the horizontal direction is unlimited, but limited to 511 in the vertical. The only limit on the number of cells, and thus the spatial resolution of the input field, is the random access memory available on the computer. The required memory is a multiple of the number of cells in the x direction * the y direction * the z direction. This multiple depends partially on the selected model output. Since there are many output options available the total number of cells cannot be directly determined. As a guide, a 128 x 128 x 64 shell can easily be run on a machine of 128 Mbytes.

There is no clear approach to setting the spatial structure of the model. Although, for example, it may be desirable to process a cloudy atmosphere using a structure of 200 x 200 100m cells in the horizontal and 60 layers in the vertical, the time for processing can be reduced to a sixteenth of the original processing time if a horizontal layer contains 50 x 50 400m cells. Additionally, processing time increases with the spatial size of the cell. Small cell sizes require a photon to traverse many cells between scattering events, thus increasing the computational time between scattering events and the eventual extinction of the photon. However, as processed in the code, adjacent cells that are homogeneous are skipped which reduces the above effect. Throughout the code many such algorithms are employed to reduce memory expense and computational time but these should be generally transparent to the user and only be a concern to those modifying the code.

An issue about the actual computer code that requires user interface is the setting of array sizes for the maximum number of cells in the x, y and z direction. The code is written in FORTRAN77 and does not employ dynamically allocated memory. It is impossible to account for every type of shell structure. For example, one run may require a cloud field of 100 x 100 x 33 cells while the other run may be simulating a flight transect with a cloud field of 4000 x 1 x 100 cells. Obviously, the array dimensions can not all be set for the maximum possible field size (i.e. 4000 x 4000 x 100). Hence, if the arrays are too small they must be modified by changing some values in the file 'sizefile.inc' and recompiling the source code. At the moment, the code can only be run on PCs and requires Microsoft FORTRAN PowerStation for compiling. The code does not need to be changed or modified for all runs, only those runs where the shell structure exceeds the default limits. The code will not run and will provide a warning if the shell structure is not properly set. More details on this issue follow in this document.

The best way of arriving at an optimum shell structure size is through some trial and error. The maximum number of cells is not an exact quantity and requires some user iteration. The model will not run if there is not enough memory available. However, as noted above, one may not want to run the maximum allowable model size since the computational time will likely be excessive. Rather a compromise must be made between size and processing time requiring experimentation to determine if the length of time until model convergence is acceptable. For very simple Monte Carlo simulations the number of photons required for predicting a desired level of error can be estimated through Bernoulli probability. However, such a determination is virtually impossible for most model runs and one must rely on the convergence criteria. The number of photons required for convergence (and thus processing time) is proportional to the square root of the number of photons used. Hence, one must carefully choose an minimum acceptable level of random error. Finally, the speed of convergence depends greatly on the wavelength being computed. For wavelengths with little absorption the processing time will be much less than for wavelengths where there is high gaseous or droplet absorption. In summation, the model should be "played" with in order to gather a sense to proper model configurations, convergence criteria and selection of inputs.

Many of the microphysical inputs to the model are the same as used in SBDART. Thus documentation for namelist INPUT is not provided here but can be found in document rt.doc. What follows is a list of the files required for running SB3D, the inputs not found in rt.doc, instructions on how to compile and run SB3D.

SB3D Files

To run SB3D a set of executable files, namelist control files, input files and a data file are required. The italicized files represent filenames that are named by the user.

Executable Files:

- Mcshell.exe** Program loops through a set of parameters (e.g. wavelength, solar zenith and azimuth angle and computational mode) calling the executable files Mcprep and Mcrun at each step.
- Mcprep.exe** Program preprocess model microphysics using same library routines as SBDART. Program must be run one wavelength at a time.
- Mcrun.exe** Program computes fluxes using Monte Carlo method from Mcprep.exe output. Program must be run one wavelength at a time.

Data Files:

- Miestorb.dat** Binary file contains pre-computed Mie scattering data for cloud droplets for use in Mcprep.exe. This file is not required, but it greatly speeds processing.

Namelist Files:

- Control.root** Namelist file for controlling model execution.
- Input.root** Namelist file for setting microphysics and model structure.

User Input Files:

- zscale.root** ASCII file containing scaling data along vertical axis. The length of the file corresponds to the number of model layers and the values are the thickness of each layer in kms. The lowest layer represents the surface and normally has a thickness of .001 km. This file will be generated if it does not exist and filled with a standard atmosphere scaling. The format is a single column of NZ length.
- mapset.root** ASCII file containing altitude (kms) of layers for output of flux data. See input variable NS documentation for details. This file will be generated if it does not exist. The format is a single column of length NS.
- radset.root** ASCII file containing radiance bin zenith and azimuth angle and cone size. See input variable NR for details. This file will be generated if it does not exist. The IDL format of the array indexing is dum(3,NR). The columns represent zenith angle (deg.) azimuth angle (deg.) and cone size (deg.).
- wl.root** Optional ASCII file containing wavelengths for processing. This file is accessed if standard wavelength looping is not used. See variable MCWLSTRT for details. The format is a single column with the length equal to the absolute value of MCWLSTRT when it is set to a negative value.
- profile** Optional ASCII file containing an atmospheric profile. See variable PRFLEFNM for details. In IDL format the array indexing is dum(4, NZ+1). The columns represent pressure (mb), temperature (K), water vapor (gm^{-3}) and ozone (gm^{-3}) in that order.

<i>clouda</i>	Optional ASCII file containing 3D cloud distribution of liquid water or ice in units of concentration (gm^{-3}) or optical thickness. Up to 5 different files can be used. See variable NZS1 and example for details. In IDL format the array indexing is <code>dum(NZT1,NX,NY)</code> . The horizontal dimensions must match that of the entire model.
<i>cldrea</i>	Optional ASCII file containing 3D cloud distribution of cloud effective radius (μm). For liquid water the numbers are positive and can vary internally from 2 to 128 μm s. For ice, the number is negative and the size must be a constant single size throughout all clouds. The actual size is specified by the variable ICE (see namelist MCINPUT) regardless of the value contained in this file. Up to 5 different files can be used. See variable NZS1 and example for details. In IDL format the array indexing is <code>dum(NZT1,NX,NY)</code> . The horizontal dimensions must match that of the entire model.
<i>cloudb</i>	Optional ASCII file containing 3D distribution of ice or drizzle in units of concentration (gm^{-3}) or optical thickness. Up to 5 different files can be used. See variable NZS2 for details. In IDL format the array indexing is <code>dum(NZT2,NX,NY)</code> .
<i>image</i>	Optional file containing grid of surface reflectance values. In IDL format the array is <code>dum(NX,NY)</code> .

INPUT

input.root input

The default namelist for the file 'Input.root' is shown below in namelist INPUT and MCINPUT. Parameters in the namelist INPUT are the same as used in SBDART and the documentation can be found in SBDART's rt.doc.

```
&INPUT
IDATM =          4
PBAR =        -1.000000
SCLH2O =       -1.000000
UW =          -1.000000
UO3 =          -1.000000
ZCLOUD =       0.000000E+00    0.000000E+00    0.000000E+00    0.000000E+00    0.000000E+00
TCLLOUD =       0.000000E+00    0.000000E+00    0.000000E+00    0.000000E+00    0.000000E+00
LWP =           0.000000E+00    0.000000E+00    0.000000E+00    0.000000E+00    0.000000E+00
NRE =           8.000000          8.000000          8.000000          8.000000          8.000000
RHCLD =        -1.000000
XRSC =          1.000000
XN2 =          -1.000000
XO2 =          -1.000000
XCO2 =          -1.000000
XCH4 =          -1.000000
XN2O =          -1.000000
XCO =          -1.000000
XNO2 =          -1.000000
XSO2 =          -1.000000
XNH3 =          -1.000000
XNO =          -1.000000
XHNO3 =         -1.000000
ZAER =         0.000000E+00    0.000000E+00    0.000000E+00    0.000000E+00    0.000000E+00
TAERST =        0.000000E+00    0.000000E+00    0.000000E+00    0.000000E+00    0.000000E+00
JAER =           0              0              0              0              0
IAER =           0
V =            23.000000
RHAER =        -1.000000
TBAER =        -1.000000
ABAER =         0.000000E+00
WBAER =         0.000000E+00
W3BAER =        0.000000E+00
GBAER =         0.000000E+00
ISALB =          0
ALBCON =        7.000000E-02
SC =           2.500000E-01    2.500000E-01    2.500000E-01    2.500000E-01
/
&MCINPUT
NX =            1
NY =            1
NZ =           33
XSCALE =        1.000000
YSCALE =        1.000000
PRFLEFNM =      -
ALBGAS =        5.000000E-01
NZS1 =          -1            -1            -1            -1            -1
NZT1 =          -1            -1            -1            -1            -1
MOD1C = -          -          -          -          -          -
MOD1S = -          -          -          -          -          -
NZS2 =          -1            -1            -1            -1            -1
NZT2 =          -1            -1            -1            -1            -1
MOD2C = -          -          -          -          -          -
MOD2S =          0              0              0              0              0
KMODE =          1
EXTLIM =        1.000000E-05
MIE =            T
CLDTYPE =        1
ICE =          -108.000000
DRZ =           128.000000
IMGFILE =      -
NR =            5
```

```

NMR =      0
NS =       5
OCNTYPE =   0
WIND =     5.000000
FOAMREF =   5.500000E-01
CCMICE =    F
CCMAER =    F
/

```

Namelist MCINPUT parameters:

NX designates the number of cells along the x axis. The minimum value is 1 and the maximum value must be 1 less than the parameter xsize listed in the compile instructions.

NY See NX.

NZ designates the number of layers along the vertical axis. The minimum value is 2 and the maximum value is 511. Compared to SBDART, the normal amount of layers is 34 since the surface is considered a layer of minimal thickness.

XSCALE is the length of all cells in the x dimension (km).

YSCALE is the length of all cells in the y dimension (km).

PRFLEFNM is the file name containing atmospheric profile data. The number of layers in the file must match the variable NZ. This file is read in when IDATM = -1.

ALBGAS is a pseudo single-scattering albedo for absorbing gas. Since gaseous absorption by definition has a single scattering albedo of 0., ALBGAS is set to a value (nominally .5) to reduce statistical variance in regions which may be surrounded by high gas concentrations. The direction of travel by the photon is not changed after a gas interaction. If ALBGAS is greater than 0., the gas extinction coefficient is rescaled by $1/(1. - ALBGAS)$.

NZS1 is a five element array that designates the lowest layer for each 3D block of liquid water content (or ice) or optical thickness that is contained in up to five data files described by input file type 'clouda'. Five different data sets can be used as input to provide the means for creating five separate cloud decks. The actual filenames of these data sets are stored in the array MOD1C as shown below. If two cloud data sets have layers that overlap, the data set last read will be the only one used for the overlapped layer. Layers which are not overlapped remain the same. The data files are read in order of the left to right in the array MOD1C. A value of -1 in NZS1 means no data.

NST1 is a five element array that designates the thickness of each 3D block of liquid water (or ice) or optical thickness. The thickness is given number of layers. A value of -1 means no data.

MOD1C is a five element string array that contains the filename for each 3D block of liquid water or ice (in terms of concentration gm^{-3}) or optical thickness) represented by file type 'clouda'. Filename is limited to 16 characters. A dash mark means no data files.

MOD1S is a five element string array that contains the filename for each 3D block of cloud droplet size distributions (file type 'cldrea') that correspond to the above cloud concentration. For each cloud concentration file there must exist a corresponding droplet size distribution file with the same dimensions. Filename is limited to 16 characters. A dash mark means no data files.

CLDTYPE designates the cloud concentration units contained in the MOD1C files. CLDTYPE =1 for optical thickness. CLDTYPE =2 for liquid water content (gm^{-3}).

Example: Stratus with overlying cirrus.

```

NX      = 10
NY      = 8
NZS1    =      2      12      -1      -1      -1
NZT1    =      3      2      -1      -1      -1
MOD1C   = 'fldlw.strat' 'fldlw.cir'   -      -      -
MOD1S   = 'fldre.strat' 'fldlw.cir'   -      -      -
CLDTYPE =2

```

This example shows that there are two separate data files. The first file 'fldlw.strat' contains a block of liquid water concentrations (gm^{-3}) that has the dimensions of 10 x 8 x 3 cells. The block will fill model layers 2, 3 and 4. The corresponding size distribution for each cell is contained in file 'fldre.strat'. The second file 'fldlw.cir' in MOD1C contains a second block of liquid water concentrations (gm^{-3}) that has the dimensions of 10 x 8 x 2 cells. This block will fill layers 12 and 13. The corresponding size distributions for each cell is contained in the file fldre.cir'.

NZS2 is a five element array that designates the lowest layer for each 3D block of ice or drizzle (in units of concentration (gm^{-3}) or optical thickness) that is contained in up to five data files described by input file type 'cloudb'. This input provides a means for mixing ice or drizzle into the cloud layers produced by file type 'clouda' above. However, this input allows only ice or drizzle of a single effective radius and allows no variation. If two cloud data sets produced by file type 'cloudb' having layers that overlap, the data set last read will be the only one used for the overlapped layer. The data files are read in order of the left to right in the array MOD2C. A value of -1 in NZS2 means no data.

NST2 is a five element array that designates the thickness of each 3D block of ice or drizzle. The thickness is given number of layers. A value of -1 means no data.

MOD2C is a five element string array that contains the filename (filetype 'cloudb') for each 3D block of ice or drizzle in units of concentration (gm^{-3}) or optical thickness. Filename is limited to 16 characters. A dash mark means no data files.

MOD2S is a five element integer array that designates if the corresponding file in MOD2C is drizzle or ice. A positive 1 equals drizzle. A negative 1 equals ice. A zero means no data.

ICE sets the effective radius for ice. This value should be a negative number. Default is $-108 \mu\text{m}$.

DRZ sets the drizzle drop size. This value is positive. Default is $128 \mu\text{m}$.

Example: Cumulus-Nimbus with drizzle and cirrus shield.

```

NX      = 10
NY      = 8
NZS1    =      3      -1      -1      -1      -1
NZT1    =      11      -1      -1      -1      -1
MOD1C   = 'fldlw.nim' -      -      -      -      -
MOD1S   = 'fldre.nim' -      -      -      -      -
CLDTYPE = 2
NZS2    =      2      10      -1      -1      -1
NZT2    =      2      4      -1      -1      -1
MOD2C   = 'fldlw.drz' 'fldlw.ice' -      -      -
MOD2S   =      1      -1      0      0      0
ICE     = -108
DRZ     = 128

```

This example shows that there is a single type 'clouda' data file and two type 'cloudb' data files. The first file 'fldlw.nim' in MOD1C contains a block of liquid water concentrations (gm^3) that has the dimensions of $10 \times 8 \times 11$ cells. The block will fill model layers 3 through 13. The corresponding size distribution for each cell is contained in file 'fldre.nim'. The first file in MOD2C 'fldlw.drz' contains a block of drizzle concentrations (gm^3) that has the dimensions of $10 \times 8 \times 2$ cells. This block will mix in drizzle with an RE equal to $128 \mu\text{m}$ into layers 2, 3 and 4. The second file 'fldlw.ice' in MOD2S will mix in ice with an RE equal to 108 into layers 10, 11, 12 and 13.

MIE defines the phase function used for cloud droplets. Mie equal to T uses Mie theory (Wiscombe, 1980). Mie equal to F uses a Henyey-Greenstein approximation. Normally, MIE should be set to T. Henyey-Greenstein is provided for making comparisons to other models. Henyey-Greenstein is always used for aerosols. Running with MIE set to T will not increase processing time when the data file miestorb.dat is found within the working directory. If not present, then computations can take considerably more time if many different effective radii are used for a cloud layer. The difference in irradiance between MIE and HG computations is not more than a few percent, but for radiance there can be a much larger difference.

KMODE defines the type of gaseous K-distribution method to be used. KMODE equal to 0 is the same as SBDART KDIST set to 1. In this mode there is a single three term K-distribution used (as done in SBDART). KMODE equal to 1 accounts for overlapping absorption lines. SBDART does not account for overlap and it is unclear if there is any added benefit to using the overlap since the LOWTRAN7 K-distribution is only an approximation. Overlaps between absorption lines occur throughout the solar spectrum, but are likely only significant near $2.7 \mu\text{m}$. At this wavelength, the absorption is already maximized and the solar input is relatively low so any error associated with not employing the overlap is probably minimal for broadband computations. For comparison with spectral measurements, however, the error may be unacceptable. The problem with using the overlap is that it can dramatically slow down processing time at certain wavelengths by a factor of 3.

EXTLIM sets the tolerance by where adjacent cells are assumed to be equal in total extinction coefficient. Default value is $1.E-05$. Raising the value may speed processing time by smoothing the field in areas of minor variability that have little effect on domain average flux. This value should be kept at the default, unless experimentation shows the increase in speed does not bias the results.

IMGFILE is a string variable holding the name for an albedo image (file type 'image') that is used to compute surface reflectance. These values do not vary with wavelength. This albedo is used when ISALB is set to 11. The size of the image must be $NX \times NY$ in size. A dash means no data.

NR

is the number of radiance bins used for computing TOA radiance as a domain average. Radiance is computed by summing all the photon weight exiting the TOA within a cone centered on a radiance vector defined by a radiance zenith and azimuth angle. The vector origin is located at the final photon scattering location and points toward the TOA. The azimuth angle uses mathematical coordinates where 0 degrees is East rather than North. The radiance vector directed from the east towards the west is considered to have a azimuth angle of 0 degrees. From the north towards the south the azimuth angle is 90 degrees. The radiance bin cone size, zenith and azimuth angle are defined in file 'radset.root.' Since the radiance represents a subset of the TOA upwelling irradiance many more photons must be processed for radiance to produce the same level of random error. The number of photons decreases with an increase in cone size but at the expense of radiance resolution.

NMR

is the number of radiance bins used for computing TOA radiance for each atmospheric column. Thus the radiance output will be a map of radiance. The zenith, azimuth and radiance cone size are the same as used for NR, but only the bins 1 – NMR are computed. This subset reduces memory requirements. Mapping radiance is very computationally expensive since the radiance is now partitioned among (NX x NY) cells. As shown below, the coordinates used for mapping is not the last photon scattering location (*) in the horizontal plane (a), but the location where the inverted radiance vector intersects the surface (b). Hence, the radiance is mapped to where a satellite would “observe” the interaction, for example, with an cloud.

NS

is the number of layers to output for mapping fluxes (both atmospheric and oceanic) for output. Rather than mapping the upwelling and downwelling irradiance and absorption for all cells in the model domain, only those cells listed in the file 'mapset.root' are stored. The layers are referenced in terms of altitude (km) and the model finds the layer top that is closest to that altitude. The upwelling and downwelling flux represents the photons that have passed through the top boundary of a specified layer. Absorption is summed between each specified layer. It is inclusive of the lower layer and exclusive of the higher layer. For example, below is a eight layer atmosphere and a three layer ocean. Altitude (as designated from the file zscale.root) and depth (fixed in code) boundaries are

represented by the layer and shown as solid lines. NS in this case is set to 4 and the values in 'mapset.root' are

[-1,0,0,5,5,16,0]

The output will produce a 4 layers of output data for (NX * NY) number of gridded cells. Upwelling and downwelling flux will be stored for depth -1 km, and altitude 0.0 km, 6.0 km and 15.0 km. Three sets of absorption grids will also be store. The first gridded set will sum the absorption of layers -1, -2 and -3. The second set will be the absorption of layers 1. The third set will sum the absorption of layers 2, 3 and 4. The fourth set will sum the absorption of layers 5, 6 and 7.

OCNTYPE	designates type of ocean surface. If ocntype equals 0 then ocean surface is Lambertian and albedo is from SBDART library. If ocntype equals 1 then ocean has 3-D wave surface and is completely absorbing once a photon penetrates the ocean surface. Scattering can still occur from foam and the air-ocean interface. There is no internal water column scattering. If ocntype equals 2 then ocean has a 3-D wave surface and internal scattering from hydrosols and phytoplankton. Yellow substance, chlorophyll and particulate matter coefficients can only be altered within the code. A setting of 2 is very time consuming and is primarily useful for remote sensing in the visible wavelengths. Currently, the ocean parameters are set for the Celtic Sea. Note: the ocean component is still experimental! Within the ocean component there is no horizontal transport of photons nor horizontal distribution of ocean constituents.
WIND	is the wind velocity (m/s) for computing 3-D ocean surface waves. Greater wind increases the angular distribution of waves and generally enhances scattering. The relationship is not straight forward since photons in the model can scatter off one wave and be intercepted by another. Default is 5 m/s.
FOAMREF	is the reflectance of ocean foam as a fraction. Default is 0.55.
CCMICE	designates if set to T, the model uses the CCM3 ice microphysics for clouds.
CCMAER	designates if set to T, the model uses the CCM3 aerosol parameterization. At the moment it is not used.

Control root file

The control file executes the SB3D model. It provides for some simple looping of input parameters. Three loops are provided. The outside loop controls the wavelength, the middle loop controls the processing mode, and the inner loop the solar geometry.

Namelist CONTROL parameters:

```
&CONTROL
MCWLSTRT = 2.500000E-01
MCWLEND = 4.000000
MCWLINC = 5.000000E-03
MCSZA = 0.000000 -1.000000 -1.000000 -1.000000 -1.000000 -1.000000
MCAZMTH = 0.000000 0.000000 0.000000 0.000000 0.000000 0.000000
MCMODE = 1 0
TOACELL = 33
RADPRC = F
MAPRAD = F
SMAPFLX = F
MAPFLX = F
MAPPTH = F
PHTN = 10000000
CONVERGE = 1
CVRGSTEP = 10000
CVRGTOL = 1.000000E-01
CVRGX = 1
CVRGY = 1
CVRGR = 1
FILEOUT = 100000
SCRNOUT = 1000
IRAN = 12345678
WATTOUT = F
/
```

MCWLSTRT designates the initial wavelength (μm) for processing. By setting this number to a negative value, wavelengths in file *wl.root* are used for processing. The number of wavelengths processed in file *wl.root* is equal to the absolute value of MCWLSTRT. Valid wavelength range is 0.25 – 5.00 μm .

MCWLEND designates the value for the final wavelength (μm) processed when wavelength looping is employed.

MCWLINC is the increment (μm) used between MCWLSTART and MCWLEND.

MCSZA is a six element array containing the solar zenith angles (deg.) to be processed. The model will increment through the array and process a run for the solar zenith indexed. A -1 prevents further looping of the solar zenith angle.

MCAZMTH is a six element array containing solar azimuth angles (deg.) that correspond to the index used in MCSZA. Valid range is from 0 to 360 degrees. The azimuth angle is expressed in mathematical terms. The solar beam directed from the east towards the west is considered to have a azimuth angle of 0 degrees. From the north towards the south the azimuth angle is 90 degrees.

MCMODE is a two element array describing the operating mode. MCMODE set to 1 uses the horizontal transport mode (3DM) and MCMODE set to 2 uses the independent pixel approximation (IPM). A -1 in the second index prevents further processing of different modes. Both modes employ the Monte Carlo method. For 3DM, a photon can travel horizontally until it reaches the edge of the model shell. At this point, the photon exits the shell and returns at the opposing boundary with the same trajectory, thus creating a cyclic boundary. For the IPM, a photon reaching the edge of a cell returns into the same cell at the opposing boundary with the same trajectory. Here, the cyclic boundary is for each cell and not the entire shell as is the case for the 3DM. The PPM mode is not an option since there are a multitude of methods for describing the average microphysical properties of a cloud field. Thus, the user must produce the average cloud field for input. The equivalent PPM mode would then be obtained by setting NX and NY to 1 and running the model in either IPM or 3DM. For faster processing for PPM, the XSCALE and YSCALE should have large values (e.g. 10000).

Example: Broadband test. – root is named ‘test’

```
MCWLSTRT = .25
MCWLEND = 4.00
MCWLINC = .005
MCSZA = 0.00      30.0      60.0      -1.      -1.      -1.
MAZMTH = 90.      90.      90.0      -1.000000      -1.000000      -1.000000
MCMODE = 1        -1
```

This example will compute 751 wavelengths from .25 to 4.00 μms in increments of .005 μms . For each wavelength, the mode will be the 3DM. Three different solar zenith angles will be processed at 0, 30 and 60 degrees. The azimuth angle will be 90 for each run. Output file names will be preceded by the root name plus solar zenith angle, processing mode and azimuth angle for identification. The first output file will have name test00H90, followed by test30I90 and test60I90.

Example: Spectral test – root is named ‘spectral’
File wl.spectral contains [.5,.93,1.51]

```
MCWLSTRT = -3
MCWLEND = 4.00
MCWLINC = .005
MCSZA = 50.0      50.0      -1      -1.      -1.      -1.
MAZMTH = 90.      180.      0.0      -1.      -1.      -1.
MCMODE = 1        2
```

This example will compute 3 wavelengths at .50, .93 and 1.50 μms . For each wavelength, the mode will be the 3DM followed by IPM. A single solar zenith angle of 50.0 degrees. Two azimuth angles will be processed at 90 and 180 degrees. Output file names will be preceded by the root name plus solar zenith angle, processing mode and azimuth angle for identification. The first output file will have the root name spect50H90, followed by spect50H18, spect50I90 and spect50I180.

TOACELL is the layer that represents the top of the atmosphere. Normally, TOACELL is set to NZ.

RADPRC processes radiance if set to T. To save processing time set RADPRC to F if radiance is not required. The maximum number of radiance bins is 50. Parameter rsize in the source code must be changed to a value equal to or greater than NR if more bins are needed. See compiling SB3D instructions.

MAPRAD maps radiance for output if set to T. This option is memory intensive and reduces the maximum number of cells available in the model shell. To use MAPRAD, the parameters, mrsize and mrysize in the source code must be set equal to or greater than NX and NY, respectively. Additionally, parameter mrysize in the source code should be equal to or greater than NMR. Default values for mrsize and mrysize is 1. See compiling SB3D instructions.

SMAPFLX	if set to T, produces upwelling and downwelling irradiance and absorption output for each cell in a layer designated in file 'mapset.root'. This option can be very memory intensive and the output should generally be viewed as qualitative rather than quantitative unless care has been used for setting convergence criteria (see below). The maximum number of layers that can be stored is set by the parameter, ssize in the source code and must be set equal to or greater than NS. Default value for ssize is 10. See compiling SB3D instructions.
MAPFLX	if set to T, produces upwelling and downwelling irradiance and absorption output for every cell within the model shell. This option is very memory intensive and the output should generally be viewed as qualitative rather than quantitative unless care has been used for setting convergence criteria (see below). To use MAPFLX the parameters, mfxsize and mfy size in the source code must be set equal to or greater than NX and NY, respectively. See compiling SB3D instructions.
MAPPTH	if set to T, produces pathlength and photon weight output for every cell. This output is of limited use, but provided for diagnostics. This option is very memory intensive and reduces the maximum number of cells available in the model shell. To use MAPPTH, the parameters, mrxsize and mry size in the source code must be set equal to or greater than NX and NY, respectively. See compiling SB3D instructions.
CONVERGE	defines the type of convergence to be used for terminating the photon process at a given wavelength. Four modes are available depending on the desired output from the model. Mode 1 converges when domain averaged TOA upwelling, surface downwelling fluxes and atmospheric absorption all individually change by less than the value indicated by CVRGTOL over three consecutive photon count intervals designated by CVRGSTEP. Mode 2 converges when domain averaged TOA radiance changes by less than the value indicated by CVRGTOL over three consecutive photon count intervals designated by CVRGSTEP. This mode converges on radiance bins numbered 1 through the value given by parameter CVRGR. Mode 3 converges using the same criteria as mode 1 but for individual atmospheric columns or groups of columns. This mode is used in conjunction with the option SMAPFLX. Convergence is on the downwelling flux of the lowest atmospheric layer in mapset.root, the upwelling flux of the highest atmospheric layer in mapset.root and the absorption between these two layers. Atmospheric columns can be grouped together as superpixels using the parameters CVRGX and CVRGY. Mode 4 works the same as Mode 3 but for radiance as in Mode 2. The maximum number of radiance bins for testing convergence for Mode 4 is three.
CVRGTOL	sets the tolerance level for convergence. If set to negative value, CVRGTOL varies inversely with the solar constant. Thus, the CVRGTOL is lowest in the visible spectrum and highest in the near-infrared. This procedure is primarily used for broadband computations to speed processing. If CVRGTOL is negative it varies according to $\text{CVRGTOL} = - ((\text{CVRGTOL} * \text{solar constant } (.46 \mu\text{m})) / \text{solar constant (wl)}).$
CVRGSTEP	The number of photons processed between checks for convergence. This value should be a multiple of (NX * NY). The proper settings of CVRGTOL and CVRGSTEP depends on the minimum acceptable level of random error. Suitable values for CVRGTOL and CVRGSTEP can usually be obtained through experimentation and monitoring of the model's output status screen. Make sure CVRGSTEP is large enough to prevent convergence from occurring at a local minima.

CVRGR	provides the number of bins required to converge before convergence is reached. If CVRGR is set to NR then all radiance bins must converge. By setting to CVRGR to a value less than NR, only the bins 1 through CVRGR must converge. This setting can be used to provide a qualitative sense to the radiance in bins that receive too few photons for reliable quantitative estimates, but are still of interest. Hence, the order of the bins in the file <i>radset.root</i> is important if CVRGR is less than NR.
CVRGX	is the number of columns grouped into a 'superpixel' along the x axis for using in convergence modes 3 and 4. CVRGX can range from 1 to NX but must be an even multiple of NX. By setting CVRGX to a value greater than 1, the time for convergence is decreased since the number of photons intercepting the superpixel is increased. The number of columns used in the 'superpixel' for analysis should be equal to or less than size number of columns that are averaged together from the output files.
CVRGY	see CVRGX.
PHTN	is the total number of fully weighted photons to be processed before termination. This value is normally set much higher than the number of photons required for convergence.
FILEOUT	is the number of photons processed between calls to output data to temporary storage files. The value should be large enough so that processing is not slowed down due to excessive file transfers. All output data are stored to file whenever convergence criteria is met or the number of photons processed equals PHTN regardless to the setting of FILEOUT. The main use for FILEOUT is to insure the storage of data for very time consuming jobs if the run needs to be stopped before completion.
SCRNOUT	is the number of photons processed between outputting model status to screen.
IRAN	is an integer seed for the random number generator. Set to a large odd integer. The seed value must be changed where runs are conducted on the same model input and the outputs combined to reduce random error.
WATTOUT	if set to T, produces output in $\text{Wm}^{-2} \mu\text{m}^{-1}$ for irradiance and $\text{Wm}^{-2} \mu\text{m}^{-1} \text{str}^{-1}$ for radiance. If set to F, all fluxes are in percent of TOA input.

Output files:

When SB3D is run, a command line root file name is entered. This root is at the end of all input files except the italicized files listed in the section INPUT FILES. For output files, the root is at the beginning of the file name and appended automatically with the solar geometry and processing mode. Subsequent runs with the same root name, solar geometry and processing mode have their output appended to the original file. The exception are the map files noted below. These files are appended with a wavelength. All files are in ASCII for internal viewing and to reduce platform crossing problems. All floating data (real) are written in single precision.

<i>*.tmp</i>	Temporary files of output data. Generally not used unless a model run is stop before being completed.
<i>iran.tmp</i>	Contains internal model data for debugging.
<i>screen.tmp</i>	File is a screen capture of model output status for remote viewing.
<i>error.tmp</i>	File contains a log of model errors for a CONTROL file and indicates if a single model run (i.e. single wavelength) was not processed correctly.
<i>profile.root</i>	File is produced by model and contains atmospheric profiles used in the computations. The output variables in column order are: real layer number real layer base (km) real layer top (km) real layer pressure (mb) real temperature (K) real water vapor content (gm^{-3}) real saturated water vapor content (gm^{-3}) real ozone (gm^{-3})
<i>root.result</i>	File contains column list of domain averaged results. All fluxes are expressed in percent of TOA input. Hence, to compute irradiance at a single wavelength, the value must be divided by 100.0 and multiplied by the solar constant. The solar constant needs to be adjusted for the cosine of the solar zenith angle. Multiple runs of the same model inputs at different wavelengths are appended together to form rows. The output variables in column order are: real wavelength (μm) real process mode (1 =3DM, 2 = IPM) real solar zenith angle (deg) real azimuth angle (deg.) real photon count real atmospheric absorption (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$) real surface absorption (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$) real toa albedo (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$) real transmission to surface (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$) real atmospheric absorption by gas (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$) real atmospheric absorption by cloud (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$) real total pathlength/total photon weight real number of voided photons (counts) -see screen sample for explanation.

root.prf File contains atmospheric profiles of irradiance, absorption and pathlength. Multiple runs of the same model inputs at different wavelengths are appended together. The output variables in column order are:

real	layer
real	atmospheric absorption (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$)
real	atmospheric absorption by gas (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$)
real	atmospheric absorption by cloud (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$)
real	layer top upwelling flux (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$)
real	layer top downwelling flux (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$)
real	layer pathlength/total photon weight
real	number of photons interacting with layer/total photon weight

At the end of the profiles for each wavelength these data in row order are added:

real	wavelength (μm)
real	process mode (1 = 3DM, 2 = IPM)
real	solar zenith angle (deg.)
real	solar azimuth angle (deg.)
real	photon count

root.ocn File contains oceanic profiles of irradiance and absorption. Multiple runs of the same model inputs at different wavelengths are appended together. For each wavelength, the data shown for the end of the profile output is attached. The output variables in column order are:

real	ocean layer
real	ocean layer base depth from surface (m)
real	ocean layer top depth from surface (m)
real	oceanic absorption (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$)
real	layer top oceanic upwelling flux (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$)
real	layer top oceanic downwelling flux (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$)

root.rad File contains radiance output in percent and the number of photons in a radiance bin. For this count (not the radiance) the weight of a photon is not considered. The counter is incremented by 1 each time a photon enters the radiance bin. However, for the radiance output (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}\text{str}^{-1}$), the weight of the photon is applied as is done for the downwelling and upwelling fluxes and absorption outputs. In IDL format the output array is (NR,2) with the first set of values (second index = 0) being radiance and the second set of values (second index = 1) being count. For each wavelength, the data shown for the end of the profile output is attached.

root.rmap File contains a mapped radiance output for the TOA in percent and the number of kilo-photons in a radiance bin. For this count the weight of photon is not considered. The counter is incremented by 1 each time a photon enters the radiance bin. However, for the radiance output (percent $\text{Wm}^{-2}\mu\text{m}^{-1}\text{str}^{-1}$), the weight of the photon is applied as is done for the downwelling and upwelling fluxes and absorption outputs. In IDL format the output array is (NX,NY,NR,2) with the first set of values (second index = 0) being radiance and the second set of values (second index = 1) being count. For each wavelength, the data shown for the end of the profile output is attached.

root.smap File contains downwelling and upwelling flux and absorption for the layers indicated in file 'mapset.root' when SMAPFLX is set to T. In IDL format the output array is (NX,NY,NS,4), with the first set of values (fourth index = 0) being absorption (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$), the second set (fourth index = 1) being upwelling flux at the top boundary of a cell (percent or

$\text{Wm}^{-2}\mu\text{m}^{-1}$), the third set (fourth index = 2) being downwelling flux at the top boundary of a cell (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$), and the fourth set (fourth index = 3) being the number of kilo-photons processed in a cell. For this count the weight of photon is not considered. The counter is incremented by 1 each time a photon enters a cell. However, the weight of the photon is applied for the downwelling and upwelling fluxes and absorption. For each wavelength, the data shown for the end of the profile output is attached.

root.fmap File contains absorption data (total, gas and cloud), and upwelling and downwelling flux for every cell within the model shell when MAPFLX is set to T. Since this file can be very large for a single wavelength, a separate file is created for each wavelength processed. In IDL format the output array is (NX,NY,NZ,5), with the first set of values (fourth index = 0) being total absorption (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$), the second set (fourth index = 1) being absorption by gas (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$), the third set (fourth index = 2) being absorption by cloud droplet or ice (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$), the fourth set (fourth index = 3) being upwelling flux at the top boundary of a cell (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$), and the fifth set (fourth index = 4) being downwelling flux at the top boundary of a cell (percent or $\text{Wm}^{-2}\mu\text{m}^{-1}$). For each wavelength, the data shown for the end of the profile output is attached.

root.pmap File contains pathlength and photon number for every cell within the model shell when MAPPTH is set to T. Photon number is the total weight of all photons entering a cell. Since this file can be very large for a single wavelength, a separate file is created for each wavelength processed. In IDL format the output array is (NX,NY,NZ,2), with the first set of values (fourth index = 0) being pathlength (km), and the second set (fourth index = 1) being photon count. For each wavelength, the data shown for the end of the profile output is attached.

COMPILING SB3D

For most applications the only time the source code needs to be compiled is when the size parameters are changed to account for large model domains or for mapping fluxes. Size parameters are set in the include file 'sizefile.inc'. Once values are changed the files mcprep.f and mcrun.f need to be recompiled. Compiling is done through Microsoft PowerStation 4.0. Below are listed the files necessary for compiling the source code. These should all be contained in a single directory. Although the mclib.lib contains the same library routines as SBDART, a few modifications were required to the library in MieV0.f and taugas.f - so do not use the SBDART library. The modifications are listed in the source code. Additional source code includes mcshell.f for producing Mcshell.exe and mkmie.f for generating the Mie data set file 'miestorb.dat'.

Source Code files:

SB3D files [mcshell.f, mcprep.f, mcshell.f, mkmie.f]

SBDART library [atms.f, cloudpar.f, errpack.f, miev0.f, refce.f, refwat.f, runmie.f, sbwk.f, solirr.f, suralb.f, tauaero.f, taugas.f]

Library – mclib.lib

Makefiles

[mclib.mak, mclib.mdp, mcshell.mak, mcshell.mdp, mcprep.mak, mcprep.mdp, mcrun.mak, mcrun.mdp, mcmie.mak, mcmie.mdp]

Data file [sizefile.inc, angle.dat]

Changing size parameters and compiling:

Start Microsoft Powerstation 4.0

- 1) Under the File heading Open sizefile.inc, edit required size parameters, save and close file.
- 2) Under the File heading Open Workspace 'mcprep.mdp'.
- 3) Under the Tools heading choose Rebuild All.
- 4) Under the File heading Close Workspace.
- 5) Under the File heading Open Workspace 'mcrun.mdp'.
- 6) Under the Tools heading choose Rebuild All.
- 7) Under the File heading Close Workspace.
- 8) Copy mcprep.exe and mcrun.exe in the Release directory to the directory used for processing.

RUNNING SB3D

SB3D can be run under any PC using windows NT or windows 95/98. See instructions below for using ESRG mc computer farm.

1) To run SB3D for the first time, copy the files listed below to a working directory.

mcshell.exe
mcprep.exe
mcrun.exe

2) Open an MSDOS window and type mcshell.exe *root* (root is any name less than 8 characters)

If SB3D does not find the file input.*root* it will create the files listed below in the same directory. It will then stop.

input.*root*
control.*root*
zscale.*root*.
mapset.*root*.
radset.*root*.
wl.*root*.

4) Edit these files according to the SB3D documentation and create field input files (if required) *clouda*, *cloudb*, *cldre*, *profile* and *image*.

5) Delete all *.tmp files by typing del *.tmp. If the file 'error.tmp' is present the job will not run. This is equivalent to a 'Are you sure?' message but a bit more demanding.

5) To run a job type mcshell.exe *root*

If an error occurs immediately it is likely a problem related to the file input.*root* with the format of the namelist being corrupted. Check around the cloud file input area in namelist.MCINPUT as the most likely source of the problem. If the problem cannot be corrected a new input.*root* file will need to be generated.

On screen the status of the run should appear. Be patient, the speed by which the screen updates depends on the settings in 'control.*root*' and the complexity of the simulation. The first set of screen output will contain information about the program mcprep.exe. Once that program is completed, status of mcrun.exe is shown. The screen for mcrun.exe also appears in the file 'screen.tmp'. If repeating a job and the original files are not needed, make sure these output files have been deleted, otherwise new output will be appended to the old data files. If the screen output seems to be quickly moving view the file 'error.tmp' in another window to check for errors. If the job needs to be halted do a CTRL-C in the running window. This may need to be done a few times since it must halt the program running (mcprep.exe and mcrun.exe) and the program mcshell.exe. A sample screen is shown on the following page.

Sample screen: Below is an example of the output provided on screen.

```
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          3DM evaluation (W/m2/um)
Wavelength      =          .550
Photons processed =        194000.
Percent completed =          1.940
Photons voided   =           0.
atm abs   srf abs   toa upw   srf dnw
107.206   680.642  1095.252   741.440

First four TOA radiance (W/m2/um/str)
385.669   382.059   390.125   385.361
First four TOA radiance counts (k)
13.563    12.990    13.052    11.526
```

The screen shows that the model is being run in the 3DM mode at a wavelength of .55 μm . 194K photons (complete weight) have been processed thus far, representing 1.9% of the maximum number of photons allowed for this run. There have been no trapped photons as indicated by the number of photons voided. A photon is terminated if the number of scattering events for the photon exceeds a specified limit in the code in order to prevent infinite looping. This occurrence is extremely rare. Generally, number of photons voided will be zero or a very small number. If greater than, for example, 0.01% of the photon count, there may be a problem with the input or code. In $\text{Wm}^{-2} \mu\text{m}^{-1}$, the atmospheric absorption, surface absorption, TOA upwelling irradiance and downwelling irradiance to the surface are shown in the next line. If RADPRC is set to T for processing radiance then the next two output lines are shown. The first line shows the TOA radiance in $\text{Wm}^{-2} \mu\text{m}^{-1} \text{str}^{-1}$ for the first 4 radiance bins provided in the file 'radset.root'. The following line provides the number of photons that have been collected in the radiance bins in units of 1000. These counts represent every contribution (both partial and fully weighted photons) to the radiance bin. If convergence is accomplished the line below is shown.

Converge at count 3.000E+06 count 2.750E+06 and count 2.500E+06 within .500%

If no convergence is achieved a the message below is printed to screen.

'Process complete - no convergence'

Running on ESRG Mcfarm.

Six PCs are located in the computer room dedicated to processing Monte Carlo simulations. To use these computers a working directory and account must be set up on each machine. The simplest method for moving files between these machines and a local PC is through NT NETWORK NEIGHBORHOOD. Since these machines are NT CLIENTS they can be access for executing jobs only through TELNET using the ATAMAN software installed on each machine. The machines are called MC1, MC2, MC3, MC4, MC5 and MC6.

To run a job copy all required files from a local PC into the working directories of each of the machines. Open a TELNET window on the local PC for each MC# machine to be used. TELNET into a machine, provide account name and password and change to the working directory. Start the job as described above in running SB3D. Status screens should appear in each telnet window. Do not close the TELNET window. It can be shrunk to an ICON but not closed, otherwise the job will be terminated. A work around to this problem is to make the job a SERVICE, but this is very complicated. File 'screen.tmp' can be viewed from a remote location to check the status of a job.

MODEL NOTES

Error messages

Error messages are self-explanatory. To preserve memory, the model is run in single precision except in sensitive areas such as calls to SBDART libraries, SBDART libraries and for accumulating photon statistics. There are consistency checks in place to check for some precision problems. Although unlikely, if a consistency error occurs, the model skips the present wavelength and writes to an error log. A fix to the error may require modifying some source code parameters. A couple of hints on what to change is given at the beginning of mcrun.f and in the error message. An error which may occur at the start of a run relates to array sizes. Normally, this problem can be fixed by editing the include file 'sizefile.inc' and recompiling.

Convergence

As noted before some of the control inputs are subjective and require a 'sense' on their proper values. Compromises must be made on model resolution and the acceptable level of random error. This requires experience and observation on how the model converges through some monitoring of the output screen. Do not set the variable CVRGSTEP too low otherwise the model may seem to converge but is actually at a local minima and may drift to a different solution.

SBDART

Model results should be checked at times with runs from SBDART using a similar input. Obviously, the results will not be the same since SBDART cannot use a 3D cloud field input, but a comparison can check for gross errors. If gross errors occur, check both inputs carefully. Make sure SBDART has KDIST set to 1. Additionally differences can occur since the phase function in SB3D has more detailed structure in the forward scattering, it has K-distribution overlap, different counting methods in regards to fluxes and model layering than SBDART, and SB3D use a stochastic method that contains random error.

Cloud layers

Cloud layers entered in namelist INPUT will overwrite clouds entered in MCINPUT.

Cloud saturation

SB3D uses the same RHCLD parameter as SBDART but differs on its application. Rather than saturating an entire atmospheric layer, only those cells occupied by a cloud are saturated to the level indicated by RHCLD. To maintain the same total water vapor amount for the entire model domain, the cells outside of the cloud are dried to compensate for the increased water vapor in the clouds. The water vapor in the dry cells will never be reduced by more than 50% of their original value. To maintain consistency in this case, the water vapor in the cloudy cells will also be reduced until the original water vapor amount is achieved. Additionally, clouds are only allowed to saturate below the tropopause.

Radiance

Radiance computations are very sensitive to the number of photons processed and can take a very long time to converge. The smaller the radiance bin, the greater the number of photons required. For some viewing angles (high zenith angles) and radiance bin sizes, it may be computationally prohibitive to compute radiance. For most applications, however, a useful radiance can be produced as long as these problems are taken into account.

Aerosols

Aerosols are sensitive to the humidity of the air. For cloudy cells, the air is assumed to be saturated to a level designated by RHCLD. Hence, within a single layer that is partly cloudy, the aerosol microphysics may vary although the horizontal distribution of the aerosols is a constant. This procedure differs from SBDART where the water vapor content in a layer is a constant value.

Ocean

The ocean component is still experimental and care should be taken in its use.

Rayleigh Scattering

For proper operation, the rayleigh scattering adjustment XRSC should be greater than .0000001.