Comparison of Modeled and Measured Shortwave Broadband Radiative Fluxes at the SGP and NSA Sites (with Special Emphasis on Diffuse Radiation)

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Introduction

The ability to model broadband radiative fluxes under clear-sky conditions has been the focus of considerable activity in the past few years. Such activity has generated numerous studies that have examined how well-modeled radiative fluxes match measurements of these quantities (Halthore et al. 1997, 1998; Kato et al. 1997, 1999; Halthore and Schwartz 2000). The results of these studies can be summarized as follows:

- Models, such as Moderate-Resolution Atmospheric Radiance and Transmittance Model (MODTRAN) 3 (Anderson et al. 1995; Berk et al. 1998; Bernstein et al. 1996), can accurately simulate the direct normal irradiance.

- At high-altitude sites (such as the Mauna Loa observatory and the South Pole), the models predict the diffuse irradiance to within the measurement error of the pyranometers that measure this quantity.

- At low-elevation, mid-latitude sites (such as the Atmospheric Radiation Measurement [ARM] Program site in Oklahoma), the models consistently overestimate the measured diffuse irradiance.

The inability of the models to predict the diffuse radiation at low-elevation, mid-latitude sites led to the hypothesis that some unknown factor, perhaps a gas, causes "excess absorption" to occur in clear atmospheres (the "Gas-X" hypothesis). This excess absorption might masquerade as a measured aerosol optical thickness (AOT) that is actually larger than the true AOT, leading to correct estimates of the direct normal radiation, but causing the calculated diffuse radiation to be too large (Halthore and Schwartz 2000).

The finding that models tend to overpredict the diffuse radiation has been coined the "diffuse discrepancy" in the scientific press. Most of the measurements that support this finding have been taken at mid-latitude sites, such as the ARM Cloud and Radiation Testbed (CART) site in Oklahoma. This raises the question as to whether the diffuse discrepancy would be found in other, different climatological regimes. An answer to this question might help identify the cause of this discrepancy.

This question brings us to the point of this short study: to apply a radiative transfer model to a sea-level Arctic site to see if the diffuse discrepancy is evident in this region, as well as assess the performance of a radiative transfer model in the Arctic. The specific model that we chose for this study is the SBDART model (Ricchiazzi et al. 1998) because it is very easy to use and past experience leads us to believe that it is reasonably accurate.

Procedure

For clear-sky conditions, the SBDART model requires as “optical inputs” an AOT at 550 nm and the columnar precipitable water. Other information, such as the total columnar ozone, can be fed to the model if this information is known. Measurements taken from Multi-filter Rotating Shadowband Radiometers (MFRSRs; Harrison et al. 1994) and Microwave Radiometers (MWRs; Liljegren 1994, 2000) provide the AOT and columnar vapor, respectively. If available, the user can supply the model detailed aerosol properties such as the wavelength dependence of both the asymmetry parameter, g, and the single-scattering albedo, ω. These quantities are usually unknown, and in their absence, the model provides the user with a number of aerosol options (rural, urban, troposphere, and the like).

Assessment of SBDART Performance Using Data from Mauna Loa

We first assessed the general performance of SBDART by using the model to simulate direct and diffuse irradiances at the Mauna Loa observatory. At this site, the atmospheric scattering is almost entirely Rayleigh; thus, the complications of aerosol scattering are absent. Kato et al. (1999) present nine cases of measurements to which they compared the performance of a two-stream model. (The direct normal irradiances were compared with simulations from MODTRAN 3 as well.) We apply SBDART to these same cases and the results are shown in Figures 1 and 2, which show the diffuse and direct normal comparisons, respectively.

Figure 1 depicts the measurements as blue circles (we like to associate the color blue with measurements because the mnemonic device, “true blue,” seems appropriate for measurements). Kato et al. (1999) estimate the uncertainty in the diffuse measurements to be about 5 to 6 W/m^2 and these uncertainty limits are shown as error bars in the figure. SBDART simulations and modeled irradiances from the two-stream model of Kato et al. (1999) are shown as orange triangles and red squares, respectively. The mean deviations between the modeled and measured values are about 1 W/m^2 (measurements – two-stream model) and about 4 W/m^2 (measurements – SBDART): the SBDART model does not do quite as well as the two-stream model; and furthermore, the SBDART simulations tend to overestimate the measurements. However, all but one of the SBDART calculations fall within the range of measurement uncertainty.

The comparison between modeled and measured direct normal irradiances portrayed in Figure 2 shows that, in general, all the model calculations fall below the measurements. The mean deviation between the measurements and the model results are 13, 15, and 22 W/m^2, for the two-stream, MODTRAN 3, and SBDART models, respectively. The measurement error is estimated to be about 1%, or about 11 W/m^2 (Kato et al. 1999), and all the model calculations are outside this limit, with the SBDART values falling under the other modeled irradiances by about 8 W/m^2, or about 0.7% of the total irradiance. Kato et al. (1999) suggest that the difference between the models and measurements are most likely due to errors in gaseous absorption. Kato et al. (1999) argue that such errors only affect simulations of the direct normal irradiance but do not cause errors in the diffuse irradiance calculations.

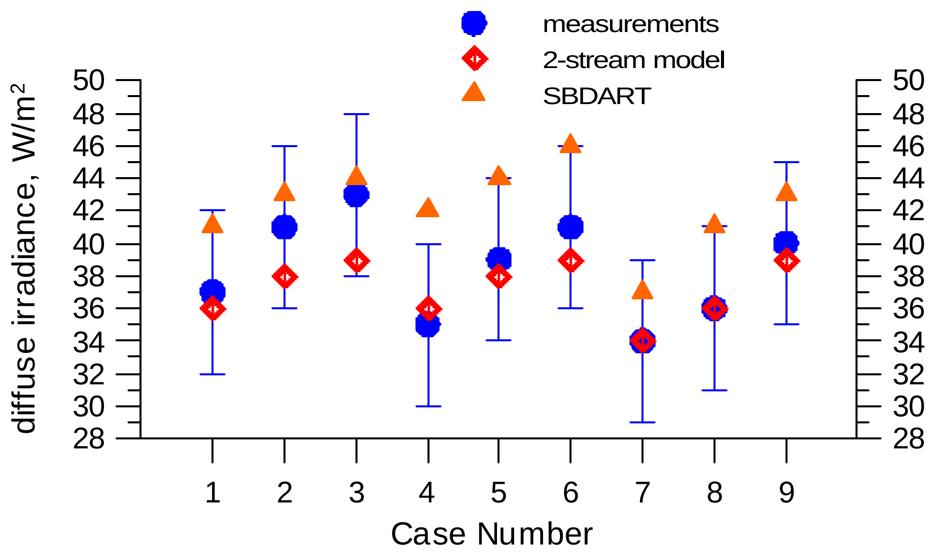

Figure 1. Comparison of measured diffuse irradiance (circles), modeled irradiance from the two-stream model of Kato et al. 1999 (diamonds), and the modeled irradiance from the SBDART model (triangles). The measurements are from Kato et al. (1999).

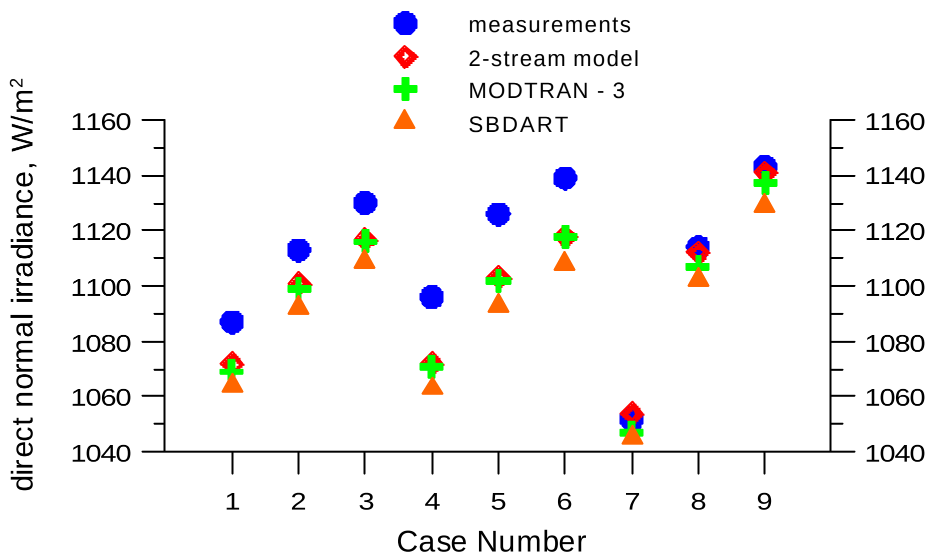

Figure 2. Comparison of measured direct normal irradiance (blue circles), and modeled direct normal irradiances: two-stream model of Kato et al. (1999), red diamonds; MODTRAN 3, green crosses; and SBDART, orange triangles.

Diffuse Irradiance Calculations for the ARM SGP Site

We now examine how well SBDART simulates diffuse irradiances measured at the ARM Southern Great Plains (SGP) site located in Oklahoma. Unlike the Mauna Loa site, the atmosphere above the ARM SGP site usually has a considerable aerosol load, thus adding an additional major complication to model calculations because aerosol scattering must be considered. Halthore and Schwartz (2000) have compared modeled diffuse irradiances, derived from the MODTRAN 3 model, with measurements of the same. We reproduce these calculations here, but instead substitute SBDART for MODTRAN.

When performing calculations in which aerosol scattering is active, SBDART requires that an aerosol scattering model be selected. We chose the "tropospheric aerosols" option. This representation of the aerosol assumes a value of g of about 0.65 and a value of ω about 0.96 at 550 nm. The results presented here are not very sensitive as to whether this particular aerosol option is used, or whether another plausible option, the "rural" aerosol, is chosen.

Once the aerosol option is selected, the calculations can proceed. Halthore and Schwartz (2000) present 40 cases in which measurements were compared with calculations at low-altitude sites, and we ran SBDART for many of these cases. For the sake of brevity, we will only show, from the grand total of 40 cases, a subset of 14 cases. The measurements contained in these 14 cases were taken during the ARM Shortwave Intensive Operational Period (IOP) of 1997: See http://www.res.sgp.arm.gov/iop/fall97. SBDART calculations of diffuse irradiance, measurements of the diffuse irradiance, and MODTRAN simulations of this quantity are shown in Figure 3. The MODTRAN model was run in either a two-stream or an eight-stream mode, but we only show calculations from the eight-stream mode.

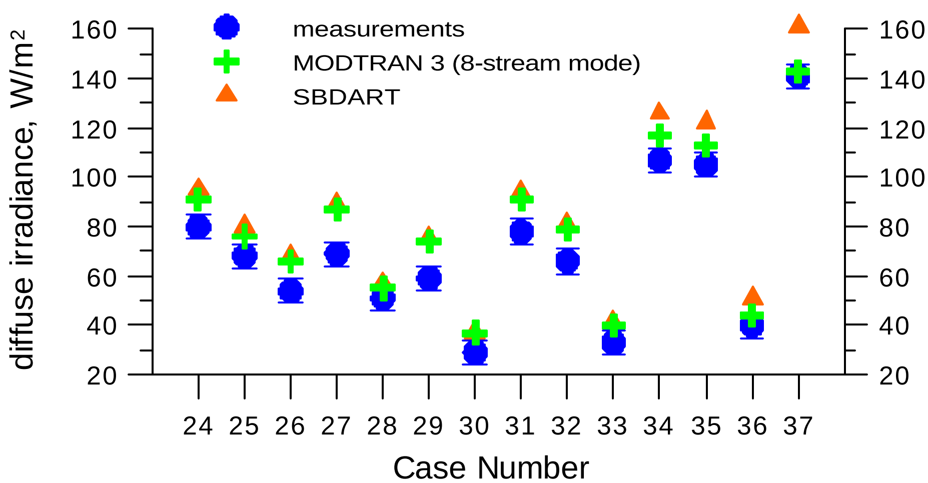

Figure 3. Diffuse irradiance, ARM SGP sites. The blue circles (with error bars) denote the measurements. The green crosses represent the MODTRAN 3 model operated in eight-stream mode. SBDART calculations are represented by the orange triangles. The data cases are numbers 24 through 37 listed in Table 1 of Halthore and Schwartz (2000); these cases were taken during ARM's 1997 Shortwave IOP.

In Figure 3, the measurements are shown by the blue circles to which error bars (5 W/m^2) have been added. All the modeled results are larger than the measured values, thus demonstrating the presence of a diffuse discrepancy at this SGP site. The average amount by which the modeled values exceed the measurements is about 14 W/m^2 for SBDART, and about 10 W/m^2 for the MODTRAN results. That SBDART overestimates the clear-sky diffuse irradiance at the SGP site was noted by Ricchiazzi et al. (1998). In a single test case that was used to illustrate the capabilities of the SBDART model, they found a large diffuse discrepancy of about 25 W/m^2, or an overprediction of almost 30%.

SBDART Calculations at the ARM NSA Site

The ARM North Slope of Alaska (NSA) site is located at Barrow, Alaska, at a latitude of about 71° N. Like the SGP site, the atmosphere above the Barrow locale can experience significant aerosol loads, and during the summer months at Barrow, the precipitable water, the AOT, and the solar zenith angles are typical of the SGP site in the late autumn, winter, and early spring seasons. However, cloud-free skies at the Barrow site are rare in the summer months. Because clear skies are necessary to determine whether a diffuse discrepancy exists, the lack of clear conditions somewhat limits the number of cases that can be studied. The algorithm of Long et al. (1999) was used to identify periods when the sky was presumably completely clear and therefore suitable for the analysis presented here.

We show the results of three cases – one case from 1998 and two from 1999. These occurred after the snow melt and the spectral albedo was determined from measurements made by the MFRSR and a downward-looking MFRSR head.

Table 1 lists the various input parameters as well as the fractional cloudiness associated with these cases. The fractional cloudiness is an average over nearly all the day (24 hours long – the sun is up all the time during these times). For 1998 no water vapor measurements were available so the climatological value was used. The lack of a precise value will affect the direct beam calculations, but as noted by Kato et al. (1999), errors in gaseous absorption in the near-IR region will not affect diffuse irradiance calculations. A few clouds occurred during July 3, 1999. These brief cloudy periods were identified using the algorithm of Long et al. (1999) and were removed from data analysis. Again, the aerosol model chosen is the "tropospheric model" and the aerosol properties associated with this model have been given above.

Table 1. Parameters relevant to the SBDART calculations for three cases of clear skies (or nearly clear skies).

Case	AOT @ 550 nm	Water vapor (cm)	Fractional cloudiness (daily average)
July 8, 1998	0.03	climatology	0
June 30, 1999	0.07	1.5	0
July 3, 1999	0.10	1.9	0.03

For all three simulations, we calculated the direct beam and diffuse irradiances over most of the day, from about 6 LST (Local Standard Time) to about 22 LST. Figure 4 shows the results of SBDART calculations for one of the case of June 30, 1999. To illustrate the sensitivity of the diffuse and direct calculations to errors in AOT, for each radiation component (i.e., direct or diffuse) we calculated the irradiance for two values of the AOT. One value is the AOT exactly as inferred from the MFRSR data. Because the AOT is thought to be in error by about ($dt \approx$) ± 0.01, we calculated another set of irradiances with the AOT reduced by this amount. Changing the AOT by -0.01 increases the direct normal irradiance by about 15 W/m^2 and reduces the diffuse irradiance by an amount less than 5 W/m^2.

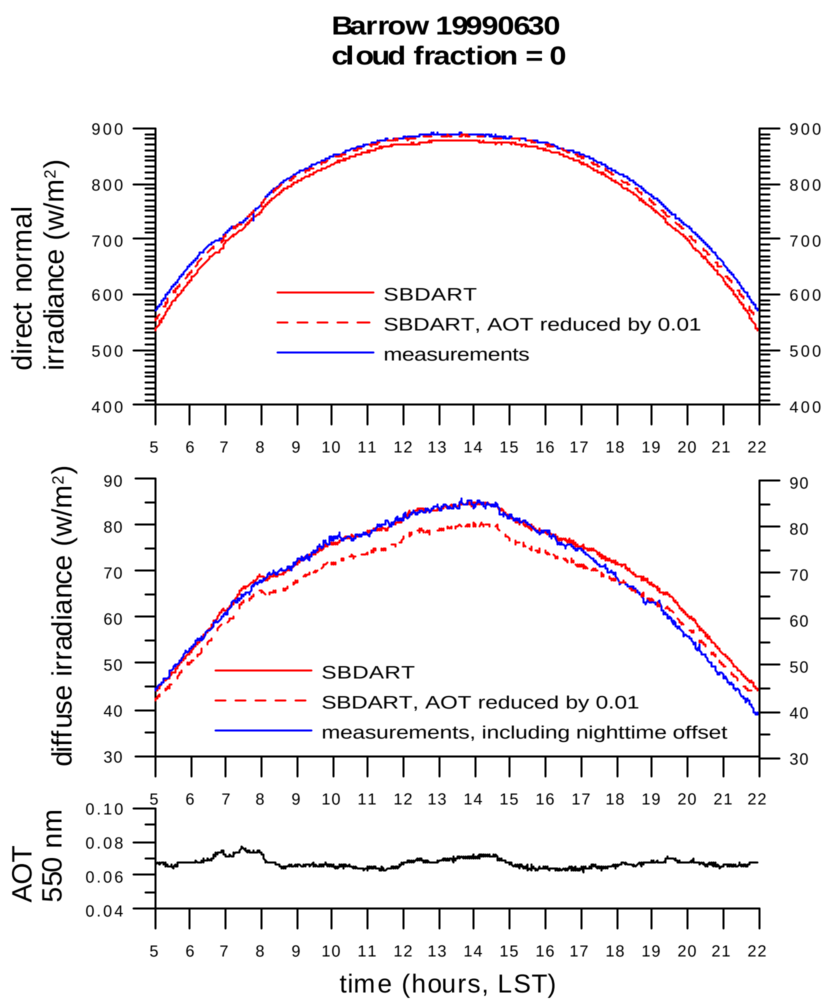

Figure 4. Calculated and measured direct irradiance (upper panel), calculated and measured diffuse irradiance (middle panel), and the AOT at 550 nm (lower panel). The measurements are shown by the blue lines and the calculations are the solid red lines (AOT unchanged), and the dotted red line (AOT reduced by 0.01). An estimated nighttime offset of 3 W/m^2 has been added to the measured diffuse irradiance.

The SBDART-calculated irradiances (red triangles) and measured irradiances (blue circles) are averaged over the day and these averaged results are shown in Figure 5. The error bars attached to the measured direct normal irradiances represent a 2% error for the Normal Incidence Pyrheliometer (NIP), the

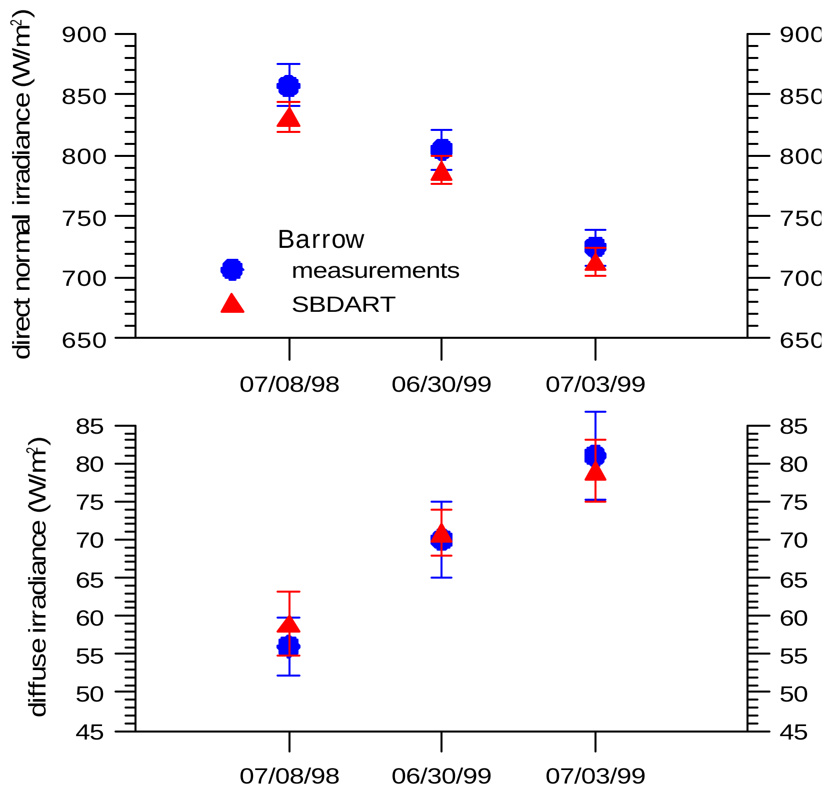

Figure 5. Measured (blue circle) and calculated (red triangles) direct normal and diffuse irradiances. Estimated errors are shown by the error bars.

instrument that measures the direct beam radiation. The error of the shaded pyranometer, which measures the diffuse irradiance, is about 7% (Tom Stoffel 2001, personal communication). Error bars have also been affixed to the calculated results that indicate the uncertainty in AOT. (For this simple analysis, we did not consider other sources of error.)

The measured diffuse irradiances have been crudely corrected for nighttime offsets. These offsets are not easily determined in the middle of the Arctic summer when the sun never sets. We calculated nighttime offsets for periods of time both before and after the presence of the "midnight sun," and the offsets observed during these times were quite small – about 3 W/m^2. This offset estimate is not very certain because it is calculated over time periods that are separated in time from the cases studied here by at least a month. We speculate that this estimate is reasonably accurate because the offsets did not vary greatly over the time periods during which we could infer them. We have added this offset to the observations.

The results shown in Figure 5 indicate that SBDART again has a tendency to underestimate the direct normal irradiance; the mean deviation between the measurements and the simulations is about 18 W/m^2. However, for the direct normal irradiance, the measurements and simulations agree to within the estimated errors of these quantities.

Curiously, unlike the diffuse discrepancy observed at the SGP site, when applied to the Barrow site the SBDART model predicts diffuse irradiances that agree quite well with the measured diffuse irradiances. For this quantity, the mean deviation between the measurements and the SBDART calculations is only about 2 W/m^2 (as opposed to a mean deviation of 14 W/m^2 witnessed at the SGP location), and the average deviation is small, about 2/3 W/m^2. This situation is far different from that observed at the SGP site, where SBDART calculations consistently overestimate the diffuse irradiance measurements. With these calculations in mind, we come to the main conclusion of this study: the data and calculations taken together provide little or no evidence of a consistent diffuse discrepancy at the ARM Barrow site.

Conclusions

In this study, we have evaluated the performance of the SBDART model by applying the model to data taken at the Mauna Loa observatory (Kato et al. 1999). In this situation the model tended to overestimate the diffuse irradiance slightly, although the calculated and measured values agreed to the level of the measurement uncertainty for eight of nine cases. When applied to the ARM SGP site, SBDART shows a consistent overestimation of the diffuse irradiances similar to that exhibited by MODTRAN 3 (Halthore and Schwartz 2000).

SBDART calculations were then performed for clear-sky cases at ARM's Barrow site. These calculations revealed that, unlike the SGP simulations, there was little or no evidence of a diffuse discrepancy at the Barrow site. The agreement between the measured and modeled diffuse irradiances at the NSA site was witnessed over ranges of AOTs, precipitable water amounts, and solar zenith angles (SZAs) that are typical of the early spring and late autumn seasons at the SGP site. Therefore, one can rule out the notion that different optical and geometric SZA properties between the two sites cause the diffuse discrepancy to be evident at the SGP site but absent at the NSA site.

The conclusion that no diffuse discrepancy exists at the Barrow site (and, by assumption, at other Arctic sites) is admittedly tenuous. Only a very limited number of cases have been examined because clear skies are not common at the Barrow site. Furthermore, the nighttime offsets that we have added to the diffuse measurements are somewhat uncertain. Even if the offsets are somewhat greater than the assumed offset of 3 W/m^2, this mistake would not cause a diffuse discrepancy to show up. In fact, the model calculations would then tend to fall *below* the measurements.

Surface albedo is another factor that might mask the signature of the diffuse discrepancy in our calculations. Although we are confident that the spectral albedos we have measured at the Barrow site are accurate, these albedos are applicable only to the land surface. The site is not far from the ocean, and after the snowmelt, the albedo of the ocean would be far different from the albedo of the land, particularly in the presence of sea ice. To what extent the albedos we have measured are truly representative of an overall, "effective" albedo is unknown. One way around this potential problem is to select some case studies before the snowmelt, when the albedo of the land and sea (ice) is about the same because these surfaces are covered with snow.

The conclusions presented here would be greatly buttressed if the calculations were repeated with another model, such as MODTRAN. If these calculations uncover no discrepancy, then an explanation must be sought as to why the discrepancy is observed in low-altitude, mid-latitude sites but apparently not in polar regions. We close tongue-in-cheek: maybe Gas-X does not exist in the Arctic!

Acknowledgment

This research was sponsored by the U.S. Department of Energy (DOE) under Contract DE-AC06-76RLO 1830 at Pacific Northwest National Laboratory. Pacific Northwest National Laboratory is operated for the DOE by Battelle Memorial Institute. The ARM Program is sponsored by the DOE.

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References

Anderson, G. P., et al., 1995: MODTRAN 3: Suitability as a flux-divergence code. In *Proceedings of the Fourth Atmospheric Radiation Measurement (ARM) Science Team Meeting*. U.S. Department of Energy, Washington, D.C. Available URL: http://www.arm.gov/docs/documents/technical/conf_9403/18_94.pdf

Berk, A., L. S. Berstein, G. P. Anderson, P. K. Acharya, D. C. Robertson, J. H. Chetwynd, and S. M. Adler-Golden, 1998: MODTRAN cloud and multiple scattering upgrades with applications to AVIRIS. *Remote Sens. Environ*., **65**, 367-375.

Bernstein, L. S., A. Berk, P. K. Acharya, D. C. Robertson, G. P. Anderson, J. H. Chetwynd, and L. M. Kimball, 1996: Very narrow band model calculations of atmospheric fluxes and cooling rates. *J. Atmos. Sci*., **53**, 2887-2904.

Harrison. L., J. Michalsky, and J. Berndt, 1994: Automated multifilter rotating shadowband radiometer: An instrument for optical depth and radiation measurements. *Appl. Opt*., **33**, 5118-5125.

Halthore, R. N., S. E. Schwartz, J. J. Michalsky, G. P Anderson, R. A. Ferrare, B. N. Holben, and H. M. Ten Brink, 1997: Comparison of model estimated and measured direct-normal solar irradiance. *J. Geophys. Res*., **102**, 23,991-30,002.

Halthore, R. N., S. Nemesure, S. E. Schwartz, D. G. Imre, A. Berk, E. Dutton, and M. Bergin, 1998: Models overestimate diffuse clear-sky surface irradiance: A case for excess atmospheric absorption. *Geophys. Res. Lett*., **25**, 3591-3594.

Halthore, R. N., and S. E. Schwartz, 2000: Comparison of model-estimated and measured diffuse downward irradiance in cloud-free skies. *J. Geophys. Res*., **105**, 20,165-21,077.

Kato, S., T. P. Ackerman, E. E. Clothiaux, J. H. Mather, G. G. Mace, M. L. Wesely, F. Murcray, and J. Michalsky, 1997: Uncertainties in modeled and measured clear-sky surface shortwave irradiances. *J. Geophys. Res.*, **102**, 25,881-25,898.

Kato, S., T. P. Ackerman, E. G. Dutton, N. Laulainen, and N. Larson, 1999: A comparison of modeled and measured surface shortwave irradiance for a molecular atmosphere. *J. Quant. Spectrosc. Radiat. Transfer*, **61**, 493-502.

Liljegren, J. C., 1994: Two-channel microwave radiometer for observations of total column precipitable water vapor and cloud liquid water path. *Fifth Symposium on Global Change Studies*, January 23-28, Nashville, Tennessee.

Liljegren, J. C., 2000: Automatic self-calibration of ARM microwave radiometer, in *Microwave Radiometry and Remote Sensing of the Environment*, P. Pampaloni, ed. VSP Press.

Long, C. N., T. P. Ackerman, J. J. DeLuisi, and J. Augustine, 1999: Estimation of fractional sky cover from broadband SW radiometer measurements. In *Proc. 10th Conf. on Atmos. Rad.*, June 28-July 2, 1999, Madison, Wisconsin.

Ricchiazzi, P., S. Yang, C. Gautier, and D. Sowle, 1998: SBDART: A research and teaching tool for plane-parallel radiative transfer in the Earth's atmosphere. *Bulletin of the American Meteorological Society*, **79**, 2101-2114.