SBDART: A Practical Tool for Plane-Parallel Radiative Transfer in the Earth's Atmosphere

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ABSTRACT

SBDART is a FORTRAN77 computer code which computes plane-parallel radiative transfer in clear and cloudy conditions within the earth's atmosphere. All important processes which contribute to the UV, visible and IR radiation fields are included. The code is a marriage of a sophisticated discreet ordinates radiative transfer module, low resolution atmospheric transmission models, and Mie scattering results for light scattering by cloud droplets. The code is well suited to handle a wide variety of problems in atmospheric radiative energy balance and remote sensing. The SBDART source code is available by anonymous FTP and on the World Wide Web.

Introduction

Until recently, the ability to compute detailed radiative quantities within the earth's atmosphere had been restricted to a relatively small group of researchers. The heavy investments of labor to compile large molecular transmission databases and the computer time required to make the complicated multiple scattering radiative transfer computuations put detailed radiative transfer (RT) computations out of reach of the general geoscience community. Within the last decade, however, the development of efficient radiative transfer algorithms and freely available gaseous transmission codes coupled with the steady improvements in computer technology have made detailed atmospheric RT within the reach of a much larger audience.

Computer codes, such as LOWTRAN (Kneizys et al, 1983) and MODTRAN (Berk et al, 1989), have provided an accurate and expedient way to compute radiation levels at low (20 cm^{-1}) and moderate (2 cm^{-1}) spectral resolutions under clear sky conditions. LOWTRAN and MODTRAN were developed primarily to address the problem of computing the atmospheric transmission in clear sky conditions. Until recently, both codes used simple two-stream radiative transfer algorithms to handle multiple scattering in overcast conditions. Besides being less accurate than more sophisticated RT treatments, two-stream methods do not provide angular radiance information, a severe limitation particularly for the interpretation of satellite remote sensing observations. Because the LOWTRAN/MODTRAN codes were intended for a highly diverse audience, the input parameters describing cloud characteristics are rather generic. For example, though several cloud types can be specified, a full range of cloud characteristics is not available. This makes it difficult to perform sensitivity studies of such basic parameters as the mean cloud drop radius. Though a multi-stream RT treatment has been implemented in the most recent version of MODTRAN, the code inherits the same generic set of cloud models as earlier versions.

In an effort to improve on the LOWTRAN/MODTRAN treatment of the cloudy atmosphere we have developed SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer). This FORTRAN computer code is designed for the analysis of a wide variety of radiative transfer problems encountered in satellite remote sensing and atmospheric radiation budget studies. The program is based on a collection of well tested and reliable physical models which have been developed by the atmospheric science community over the past few decades.

The efforts we have put into constructing SBDART has resulted in the compilation of a fairly complete and easy to use set of RT subroutines. Because of their modularity and ease of use these subroutines provide a good starting point for researchers interested in developing their own RT codes. For example, we have taken advantage of this foundation in developing a Monte Carlo RT code to handle horizontal cloud heterogeneity (O'Hirok and Gautier, 1996). Because both codes are based on a common set of micro-physical models it is a simple matter to use SBDART to validate the operation of the Monte Carlo code.

In Section 1 we discuss the key components of SBDART and the models on which they are based. Next, in Section 2 we discuss how to download SBDART, what is included in the package and other issues related to program installation. In Section 3 we conclude with several real-world applications of SBDART.

1. Physical Models

Scattering by Cloud Droplets

Clouds are a major modulator of the earths climate, both by reflecting visible radiation back to space and by intercepting part of the infrared radiation emitted by the Earth and re-radiating it back to the surface. The computation of radiative transfer within a cloudy atmosphere requires knowledge of the scattering efficiency, $\mathbf{Q}_{eff}$, the single scattering albedo, ω, which is the probability that an extinction event scatters rather than absorbs a photon, and the asymmetry factor, **g** which indicates the strength of forward scattering. We have computed these parameters using a Mie scattering code (Stackhouse, 1991) for spherical clouds droplets having a log-normal size distribution and an effective radii, $\mathbf{R}_{\mathbf{eff}}$, in the range 2 to 128 μm. (The effective radius is the ratio of the third and second moments of the droplet radius distribution.) To allow analysis of radiative transfer through cirrus clouds we also also include the scattering parameters for spherical ice grains of a fixed size distribution with $\mathbf{R}_{\mathbf{eff}}$ = 106 μm. For flux calculations we use the Henyey-Greenstein approximation of the scattering phase function. This parameterization depends only on the asymmetry factor, and has been shown to provide good accuracy when applied to radiative flux calculations (van de Hulst, 1968; Hansen, 1969).

Molecular Absorption

SBDART relies on low resolution band models developed for the LOWTRAN 7 atmospheric transmission code (Pierluissi and Marogoudakis, 1986). These models provide the clear sky atmospheric transmission from 0 to 50000 cm^{-1} and include the effects of all radiatively active molecular species found in the earth's atmosphere. The models are derived from detailed line-by-line calculations which are degraded to 20 cm^{-1} resolution for use in LOWTRAN. This translates to a wavelength resolution of about 5 *nm* in the visible and about 200 *nm* in the thermal infrared.

Because these band models represent rather large wavelength bands, the transmission functions do not necessarily follow Beers law; i.e., the fractional transmission through a slab of material depends not only on the slab thickness but also on the amount of material penetrated before entering the slab. To allow use of these transmission functions with DISORT (which assumes Beers law behavior), the band models are approximated with a three-term exponential fit (Wiscombe and Evans, 1977).

Standard Atmospheric Profiles

We have adopted six standard atmospheric profiles which are intended to model the following prototypical climatic conditions: tropical, mid-latitude summer, mid-latitude winter, sub-arctic summer, sub-arctic winter and US62. These model atmospheres (McClatchey et al, 1971) have been widely used in the atmospheric research community and provide standard vertical profiles of pressure, temperature, water vapor and ozone density. In addition, the user can specify their own model atmosphere based on, for example, a series of radiosonde profiles. The concentration of trace gases such as CO_2 or CH_4 are assumed to make up a fixed fraction (which may be specified by the user) of the total particle density.

Standard Aerosol Models

Atmospheric aerosols have a significant effect on atmospheric radiation and cloud microphysics. Due to a lack of information on their global distribution, they are considered a major uncertainty in climatic global change. For example, it has been postulated that anthropogenic sulfate aerosols may reduce the surface insolation sufficiently to partially offset the effects of increasing levels of greenhouse gases. SBDART can compute the radiative effects of several common boundary layer and upper atmosphere aerosol types. In the boundary layer, the user can select either rural, urban, or maritime aerosols. These models differ from one another in the way their scattering efficiency, single scattering albedo, and asymmetry factors vary with wavelength. The total vertical optical depth of boundary layer aerosols is derived from user specified horizontal meteorologic visibility at 0.55 μm and an internal vertical distribution model. In the upper atmosphere up to 5 aerosol layers can be specified, with radiative characteristics that model fresh and aged volcanic, meteoric and the climitologic tropospheric background aerosols. The aerosol models included in SBDART were derived from those provided in the 5s and LOWTRAN7 computer codes.

Discreet Ordinate Radiative Transfer

The radiative transfer equation is numerically integrated with DISORT (DIScreet Ordinate Radiative Transfer, Stamnes et al, 1988). The discrete ordinate method provides a numerically stable algorithm to solve the equations of plane-parallel radiative transfer in a vertically inhomogeneous atmosphere. The intensity of both scattered and thermally emitted radiation can be computed at different heights and directions. SBDART is configured to allow up to 40 atmospheric layers and 16 radiation streams (16 zenith angles and 16 azimuthal modes).

Standard Ground Reflectance Models

The ground surface cover is an important determinant of the overall radiation environment. In SBDART six basic surface types -- ocean water, lake water, clear water, vegetation, snow and sand -- are used to parameterize the spectral reflectivity of the surface. The spectral reflectivity of a large variety of surface conditions is well approximated by combinations of these basic types. For example, the fractions of vegetation, water and sand can be adjusted to generate a new spectral reflectivity representing new/old growth, or deciduous vs evergreen forest. Combining a small fraction of the spectral reflectivity of water with that of sand yields an overall spectral dependence close to wet soil.

2. SBDART Installation

SBDART is supplied as a FORTRAN77 compatible source code. The distribution package can be obtained via anonymous FTP by downloading all files found in icess.ucsb.edu:/pub/esrg/sbdart. Users wishing to "test drive" SBDART before trying to install it can do so using their net browser. Just connect to http://arm.mrcsb.com/sbdart/ and follow the simple instructions.

All source code modules are contained within a single file, sbdart.f, and generation of an executable is simply a matter of compiling this file with a FORTRAN77 compiler. Many FORTRAN compilers have an option to force all REAL declarations, constants, functions, and intrinsics to be internally interpreted as DOUBLE PRECISION. This option should be used if your computer system represents REAL numbers with 32 bit words. The distribution package includes an on-line input documentation file, rt.doc, which fully describes all input parameters. Also included is disort.doc which was provided to us by Stamnes and documents some of the important parameters used in the DISORT radiative transfer module. Finally, to simplify code validation, we have included a set of csh command files, cmd.1, cmd.2, cmd.3, cmd.4, cmd.5, and the resultant output files sbout.1, sbout.2, sbout.3, sbout.4, and sbout.5, which correspond to the five sample problems given below. The results obtained for the five sample problems should be compared with the contents of these files to ensure the code is operating properly.

The SBDART distribution package does not contain any graphics software. However, the output data formats are simple and the development of automatic graphics postprocessor should be straightforward. To limit the amount of superfluous output, most of the standard output formats do not include any descriptive labeling information. Though labeling text makes it easier to visually inspect output, it also increases the size of the output file and tends to complicate the design of postprocessing code. In most cases only a few quantities are output for each radiative transfer calculation. For example, the data written for standard output, IOUT=10 (probably the most used), consists of only 9 quantities. The on-line document, rt.doc, contains descriptions of all the standard output formats.

The SBDART Input File

User inputs are handled with FORTRAN NAMELIST input. Even though NAMELIST input is not part of the FORTRAN77 standard, it is an extremely common extension available on most modern FORTRAN compilers, and is part of the Fortran 90 standard. A significant advantage of NAMELIST input is that not all elements of an input block need be specified by the user. This feature makes SBDART fairly easy to learn. Since most of the code inputs have been initialized with reasonable default values, a novice user can quickly learn how to use the code, concentrating first on specifying just a few interesting input parameters. As an added convenience, if the file INPUT does not currently exist in the current working directory when SBDART is executed, the program will create it, filling in default values of all the NAMELIST parameters.

The SBDART input file is named INPUT (must be upper case on case sensitive operating systems). This file consists of two NAMELIST blocks $INPUT and $DINPUT (some systems require that an ampersand "&" be used in place of the dollar sign). Parameters in the DINPUT block are more closely related to operating details of the DISORT radiative transfer module, while those in INPUT are more general parameters which specify such things as the model atmosphere, the wavelength range, or output quantity options. The on-line file, rt.doc, provides a full description of the SBDART's input parameters.

3. EXAMPLES

In this section we present several real-world examples of how to use SBDART. To keep the discussion as clear as possible, the instructions given below are for operation on a UNIX system.

Example 1.

As a first example, here is an input file which causes SBDART to compute the downwelling spectral surface irradiance from 0.25 to 1.0 μm.

```
$input
   idatm=4,   isat=0, wlinf=.25, wlsup=1.0, wlinc=.005, iout=1,
 $end
```

Shell script cmd.1, which is included in the distribution package, writes these lines into file INPUT and pipes the SBDART output into file out.1. This example can be run by executing the shell script cmd.1. The run time for this example is about 5 seconds on our DEC Alpha workstation.

The out.1 file contains the SBDART output for the IOUT=1 standard output format (see rt.doc). In this format each output record corresponds to a single wavelength. Columns 1 through 8 are: the wavelength (μm), filter value (unity in this example), the downwelling solar flux at the top of the atmosphere (TOA, W cm^{-2} μm^{-1}), the TOA upwelling radiant flux, the TOA direct solar flux, the downwelling radiant flux at the surface, the upwelling radiant flux at the surface, and the direct solar flux at the surface. The results for this first example are shown in Figure 1. The best way to verify if SBDART is operating correctly is to use a standard graphics package to read out.1 and compare the results visually. The plot of surface irradiance versus wavelength provides a good test. The two plots should be nearly identical. (NOTE: due to the differences in math libraries used on different computer systems, a comparison of the output files with UNIX "diff" is bound to show some differences, but if SBDART is operating properly the numerical differences will be quite small.)

Example 2.

Most of the interesting applications of SBDART require that the code be repeatedly executed to obtain output values which represent the full range of the total input parameter space. For example, to investigate how surface irradiance depends on the combined effects of cloud optical depth and surface albedo, SBDART must be executed in a doubly nested loop, over these two parameters. In practice, the easiest way to implement this is to use a shell script to perform the looping. The distribution package contains a simple csh script, cmd.2. For each iteration of the nested loops, this shell script writes out a new version of INPUT and runs SBDART, appending its output to file out.2. Results for this run are shown in Figure 2.

Example 3.

The total precipitable water vapor amount in the atmosphere can be estimated from the ratio of observed fluxes of a narrow band (say, about 10 *nm* wide) and a broader band (≈50 *nm* wide) both centered on the water vapor absorption band at 0.936 μm (Frouin et al, 1990). The method relies on the notion that the ratio of narrow and broad bands should be relatively insensitive to surface properties. In fact, one would expect exact cancelation of the surface signature when the surface spectral reflectance varies linearly with wavelength in the vicinity of 940 *nm*. To illustrate this method with SBDART we compute this ratio as a function of column precipitable water (from 0 to 5 g/cm^2) over sand and vegetation in clear conditions. The results are shown in Figure 3.

Example 4.

Nakajima and King (1990) have developed a method for retrieving cloud optical depth and cloud drop effective radius from measurements in two spectral regions: a non-absorptive band for which the cloud single scattering albedo is very close to one and an absorptive band with a smaller single scattering albedo. We illustrate their technique by computing the TOA irradiance at 0.55 μm (non-absorptive band) and 2.16 μm (absorptive band) for cloud optical depths, τ = 0,1,2,4,8,16,32,64 and for cloud drop effective radius, $\mathbf{R}_{\mathbf{eff}}$ = 2,4,8,16,32,64,128. The results are shown in Figure 4.

Example 5.

In this final example we illustrate how SBDART can be used to compute the radiance seen by an exo-atmospheric sensor viewing a solid layer of stratus cloud over an ocean surface. The solar zenith angle is 60 degrees, and the sensor bandpass is centered at

0.72 μm. Consider four cloud cover situations: optical depth 5 or 30 combined with cloud base height of either 1 or 5 km. This example can be executed with script cmd.5.

Radiance information is obtained by specifying IOUT=20 (TOA radiance output), entering non-zero values for the input parameters NZEN and NPHI, and by setting values for UZEN and PHI, which are the zenith angles and relative azimuth angles at which the radiance information is output. In previous examples, the input parameter NSTR, which sets the number of internal radiation streams, was left at its default value of 4 (4 polar angles and 4 azimuthal modes). While 4 streams is adequate for irradiance computations (irradiance predictions with NSTR=4 are within a percent of calculations performed with a greater number of streams), radiance predictions require more streams to better resolve the angular dependence of the radiation field. As a result, the calculation of radiance takes much longer than irradiance.

The IOUT=20 output format provides the same irradiance information as produced by examples 2, 3 or 4 and is supplemented by the radiance output quantities. The IOUT=20 output format is fully described in the rt.doc online document. In Figure 5, we show contour plots of the radiance in the upper hemisphere as a function of zenith angle and relative azimuth angle. The four frames correspond to: a) low thin cloud; b) low thick cloud; c) high thin cloud; d) high thick cloud.

4. Conclusion

SBDART is a practical approach to solving plane-parallel radiative transfer problems within the earth's atmosphere. It is based on well tested atmospheric models and provides a reasonable starting point for the development of new modeling capabilities. Its extensive set of input/output options allows investigation of a great variety of atmospheric radiation problems. We have successfully applied SBDART to problems in satellite remote sensing and radiation budget analysis and are currently developing a version with higher spectral resolution.

References

Berk, A., L.W. Bernstein, D.C. Robertson "MODTRAN: A moderate resolution model for LOWTRAN 7." Philips Laboratroy, Report AFGL-TR-83-0187, Hanscom AFB, MA. 1983.

Frouin, R., P.Y. Deschamps, P. Leomte, "Determination from space of atmospheric total water vapor amounts by differential absorption near 940nm: Theory and airborne verification." Journal of Applied Meteorology, 29, 448-460, 1990

Kneizys, F.X., E.P. Shettle, W.O. Gallery, J.H. Chetwynd, L.W., Abreu, J.E.A. Selby, S.A. Clough and R.W. Fenn, "Atmospheric transmittance/radiance: computer code LOWTRAN 6." Air Force Geophysics Laboratroy, Report AFGL-TR-83-0187, Hanscom AFB, MA. 1983.

McClatchey, R.A., R.W. Fenn, J.E.A. Selby, F.E. Volz, J.S. Garing, 1972. "Optical properties of the atmosphere." (third edition), Air Force Cambridge Research Laboratories, Report AFCRL-72-0497.

Nakajima T. and M.D. King, "Determination of theoretical thickness and effective particle radius of clouds from reflected solar radiation measurements, part I: theory." Journal of the Atmospheric Sciences, 47, 1878-1893, 1990.

Pierluissi, J.H., and C.E. Maragoudakis, "Molecular transmission band models for LOWTRAN." AFGL-TR-86-0272, AD A180655.

Stackhouse, P, private communication, 1991. Dr. Stackhouse supplied the Mie scattering code we used to generate lookup tables of the cloud scattering parameters used in SBDART. Dr. Stackhouse can be contacted at Colorado State University.

Stamnes, K., S. Tsay, W. Wiscombe and K. Jayaweera, "Numerically stable algorithm for discrete-ordinate-method radiative transfer in multiple scattering and emitting layered media." Appl. Opt., 27, 2502-2509, 1988.

Tanre, D., C. Deroo, P. Duhaut, M. Herman, J.J. Morcrette, J. Perbos and P.Y. Deschamps, "Description of a computer code to simulate the satellite signal in the solar spectrum: the 5S code." Inter. J. Remote Sensing, 11, 659-668, 1990.

Wiscombe, W.J., J.W. Evans, "Exponential-sum fitting of radiative transmission functions. " Journal of Computational Physics, 24, 416-444, 1977.

Figure Captions

Figure 1. Spectral radiance at the top of the atmosphere (TOA) and at the surface in the spectral range 0.2 to 1.0 μm. SBDART's maximum spectral resolution (set by the LOWTRAN transmission models) is 20 cm^{-1}, somewhat greater than shown in this figure.

Figure 2. Surface irradiance at 0.55 μm for a solar zenith angle of 30° and for cloud optical depths between 0 and 64. The downwelling irradiance increases with larger values of surface albedo due to multiple reflection between the surface and the cloud layer.

Figure 3. Ratio of the upwelling irradiances in a narrow and a broad band centered on the water vapor absorption feature at 0.940 μm. Though the reflectance properties of sand and vegetation are quite different in the near IR, significantly affecting the upwelling irradiance at 0.94 μm, the irradiance ratio of the narrow and broad bands essentially cancels this variation and allows retrieval of the column water vapor amount.

Figure 4. A comparison of upwelling irradiance at 0.55 μm and 2.16 μm at the top of the atmosphere (TOA). Both wavelengths are strongly scattered by cloud droplets. However, whereas visible radiation is not absorbed by cloud drops, the radiation at 2.16 μm is strongly absorbed and hence is sensitive to cloud drop effective radius. This difference in response to these basic cloud properties allows a simultaneous retrieval of both cloud optical depth and drop effective radius.

Figure 5. The angular radiance distribution at the top of the atmosphere for, a) low-thin, b) low-thick, c) high-thin and d) high-thick clouds. The propagation direction of the scattered radiation is indicated on a polar grid of zenith angle and azimuth. The solar zenith and azimuth is 60° and 180°. The direction closest to the forward lobe of the scattering phase function is towards zero azimuth (toward the left).