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

Authors

Paul Ricchiuzzi, Shiren Yang, and Catherine Gautier

Earth Space Research Group
Institute for Computational Earth System Science
University of California, Santa Barbara

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Introduction

SBDART (Santa Barbara DISORT Atmospheric Radiative Transfer) is a FORTRAN computer code designed for the analysis of a wide variety of radiative transfer problems encountered in satellite remote sensing and atmospheric energy budget studies. The program is based on a collection of highly developed and reliable physical models, which have been developed by the atmospheric science community over the past few decades. The following discussion is a brief introduction to the key components of the code and the models on which they are based.

Cloud Model

Clouds are a major modulator of the earth's climate, both by reflecting visible radiation back out 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, the single scattering albedo,

which is the probability that an extinction event scatters rather than absorbs a photon, and the asymmetry factor, which indicates the strength of forward scattering. SBDART contains an internal database of these parameters for clouds composed of spherical water or ice droplets. This internal database was computed with a Mie scattering code and covers a range of particle size effective radius in the range 2 to 128 μm . (The effective radius is the ratio of the third and second moments of the droplet radius distribution). By default, the angular distribution of scattered photons is based on the simple Henyey-Greenstein parameterization, but more detailed scattering functions may be input as desired. (The Henyey-Greenstein approximation has been shown to provide good accuracy when applied to radiative flux calculations (van de Hulst, 1968; Hansen, 1969).

Gas Absorption Model

In its standard mode of operation SBDART relies on low resolution band models developed for the LOWTRAN 7 atmospheric transmission code (Pierluissi and Marougdakis, 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 were derived from detailed line-by-line calculations which were 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 bins, 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. In order to allow these transmission functions to be used with DISORT (which assumes Beers law behavior), the band models are approximated with a three term exponential fit (Wiscomb and Evans, 1977).

A capability to read high resolution k-distribution optical depths from a disk file was introduced in SBDART version 2.0. This mode of operation is less convenient to use than the standard approach, as it requires use of another program, which accesses a large spectral database to generate the high resolution files. However, it has the advantage of removing limitations in the ultimate spectral resolution available with SBDART. The ancillary programs, [CKLW](#) and [CKSW](#), may be used to create these high-spectral resolution optical depth files. These programs have not been exercised as thoroughly as SBDART. For now, they should be considered experimental.

Extraterrestrial Source Spectra

To facilitate comparison with other radiative transfer codes, SBDART may be run with any of three extraterrestrial solar spectrum models. The default is to use the LOWTRAN-7 solar spectrum (Thekeakara, 1974). This model is based on measurements between 300 and 610nm

and uses a λ^{-4} power law for longer wavelengths. Optionally, SBDART may be run with the solar models used in 5s (Tanre et al. 1990) or MODTRAN-3. The MODTRAN-3 model is probably the most accurate. It is a composite of information gathered by several different spectral measurement campaigns. For wavelengths between 174 and 351nm the spectral information is based on observations made with the Solar Ultraviolet Spectral Irradiance Monitor flown on Spacelab 2 (VanHoosier et al. 1988). Wavelengths between 351 and 868nm are based on the results of Neckel and Labs (1984). The observations of Wehrli (1985) are used for wavelengths between 0.868 and 3.226 μ m. And finally, for wavelengths greater 3.23 μ m, the longwave power law dependence of LOWTRAN-7 (Thekeakara, 1974) is used.

Standard Atmospheric Models

We have adopted six standard atmospheric profiles from the 5s atmospheric radiation code which are intended to model the following typical climatic conditions: tropical, midlatitude summer, midlatitude winter, subarctic summer, subarctic 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 CO₂ or CH₄ are assumed to make up a fixed fraction (which may be specified by the user) of the total particle density.

Standard Aerosol Models

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 μ m 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 climologic tropospheric background aerosols. The aerosol models included in SBDART were derived from those provided in the 5s (Tanre, 1988) and LOWTRAN7 computer codes (Shettle and Fenn, 1975).

Radiative Transfer Equation Solver

The radiative transfer equation is numerically integrated with DISORT (DIScret 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 65 atmospheric layers and 40 radiation streams (40 zenith angles and 40 azimuthal modes).

Surface Models

The ground surface cover is an important determinant of the overall radiation environment. In SBDART six basic surface types -- ocean water (Viollier, 1980), lake water (Kondratyev, 1969), vegetation (Manual of Remote Sensing), snow (Wiscombe and Warren, 1980) and sand (Staetter and Schroeder, 1978) -- 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.

SBDART Installation

The [SBDART](#) distribution package, is supplied in a single tar file. To expedite web transfers, the file is compressed using [gzip](#), available at no cost from the Free Software Foundation. Since a Unix makefile is included in the tar file, SBDART installation is straightforward on a Unix system:

```
unix> gunzip sbdart_2.4.tar.gz
unix> tar xvf sbdart_2.4.tar
unix> make
```

On a Windows PC a similar procedure could be used if the freely available Unix-like environment provided by [Cygwin](#) has been installed. Otherwise [Winzip](#) may be used to extract the source files from the compressed tar file. The final step is to import the source files into the interactive development environment (IDE) of your Fortran compiler.

The tar file also includes a UNIX shell script, `test_runs`, that directs SBDART to produce output corresponding to the five sample problems given below. The output is written to files `sbchk.1`, `sbchk.2`, `sbchk.3`, `sbchk.4` and `sbchk.5`. The contents of these files should be compared to the corresponding files provided in the release package, named `sbout.1`, `sbout.2`, `sbout.3`, `sbout.4`, and `sbout.5`, which were generated by SBDART on our DEC Alpha workstations.

Also included in the tar file is [rt.doc](#), a plain text file which fully describes all input parameters. A separate file, `disort.doc`, is also included that documents some of the important parameters used in the DISORT radiative transfer module.

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. [rt.doc](#) contains descriptions of all the standard output formats.

The SBDART Input File

User inputs are handled with FORTRAN NAMELIST input. A significant advantage of NAMELIST input is that not all elements of an input block need be specified by the user. Since, most of the code inputs have been initialized with reasonable default values, a new user can quickly learn how to use the code, concentrating first on specifying just a few interesting input parameters. The default state of input parameters may be determined by removing INPUT from the current working directory. When SBDART detects the absence of file INPUT, it will print the default settings of all input parameters. This output may be redirected to a file for editing.

The SBDART input file is named INPUT (must be upper case on case sensitive operating systems). This file consists of a single NAMELIST block, &INPUT.

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 the UNIX operating system.

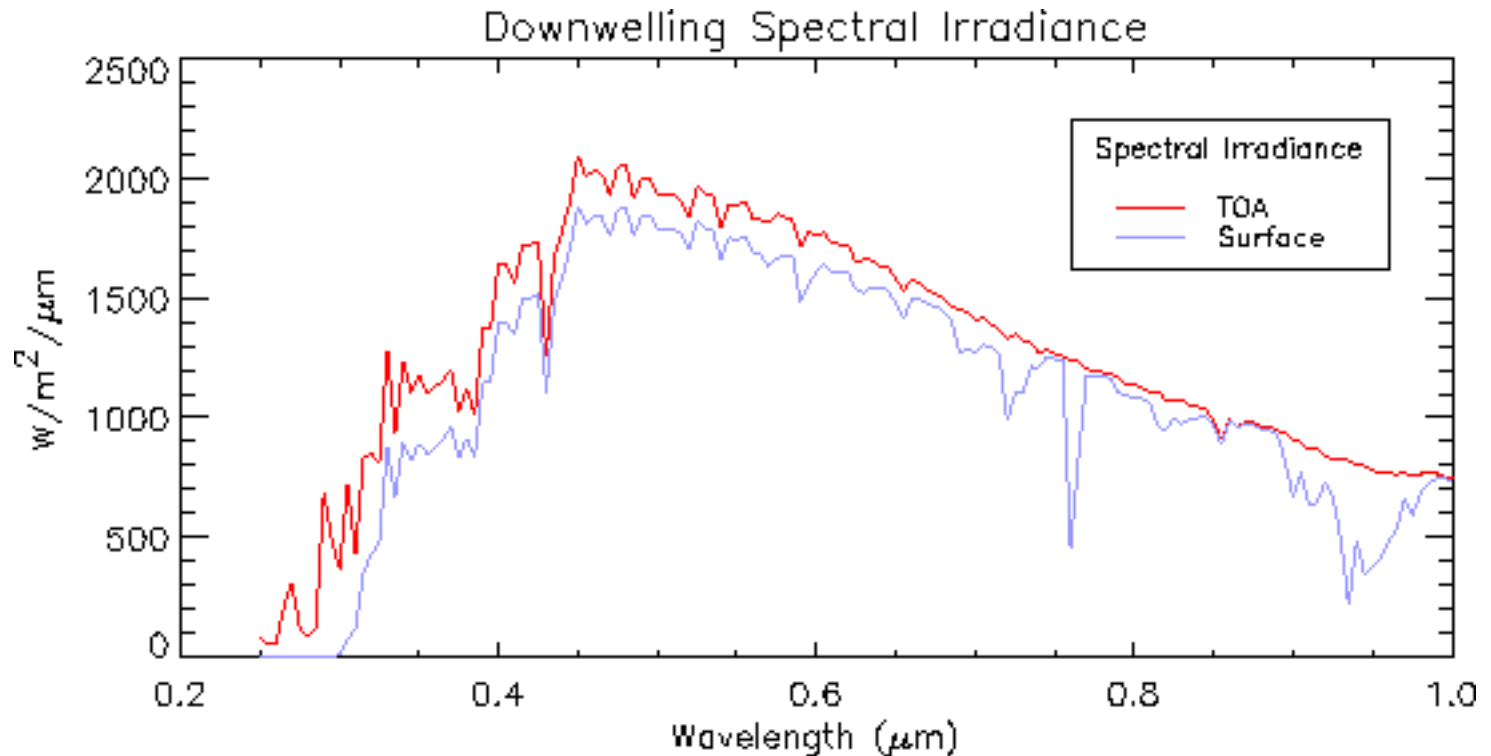
Example 1.

As a first example, here is an input file which causes SBDART to compute the 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
```

The sbout.1 file contains the SBDART output corresponding to this input. 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,

$W m^{-2} \mu m^{-1}$), 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 below. A good way to verify that SBDART is operating correctly on your system is to use your favorite graphics software to read about.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 these 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 approximately 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. Here is a simple UNIX sh script to perform the optical depth, surface albedo problem :

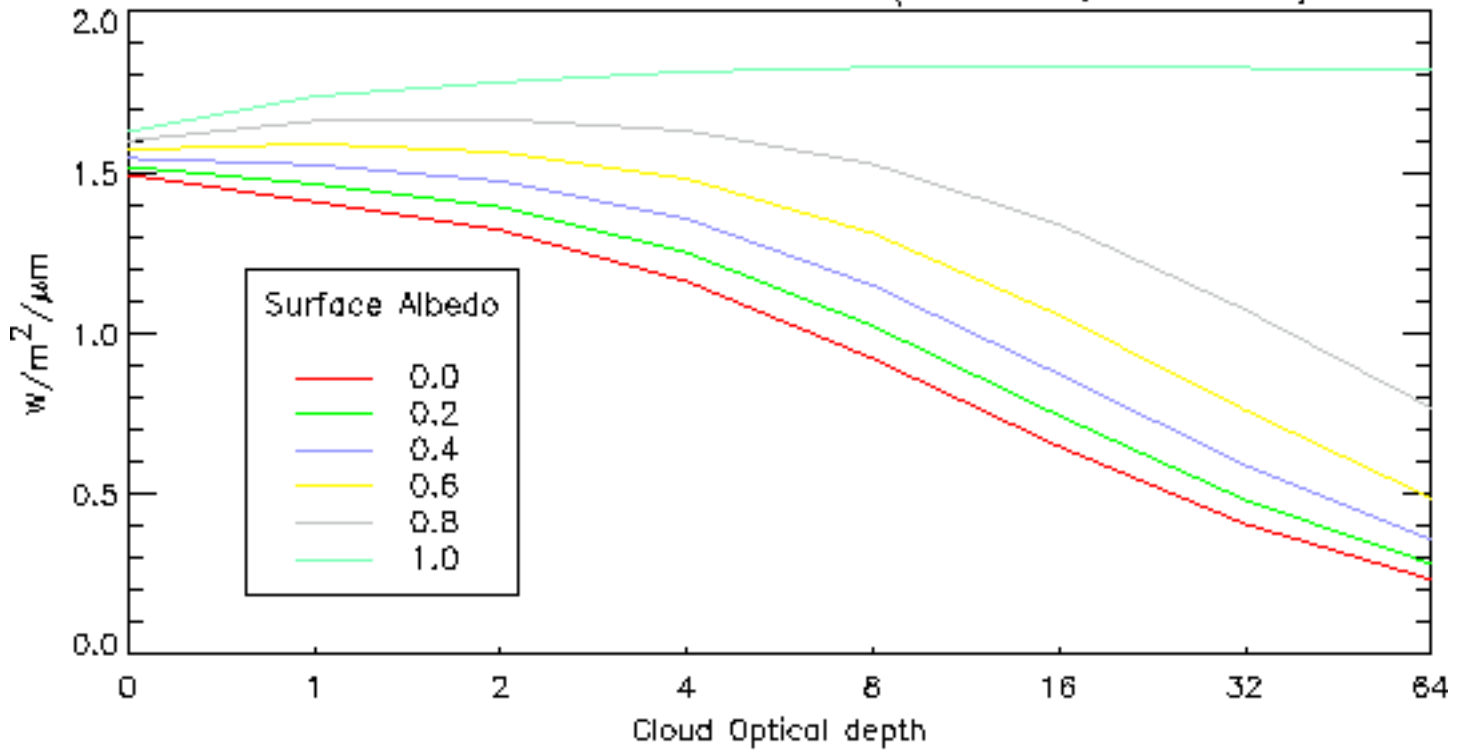
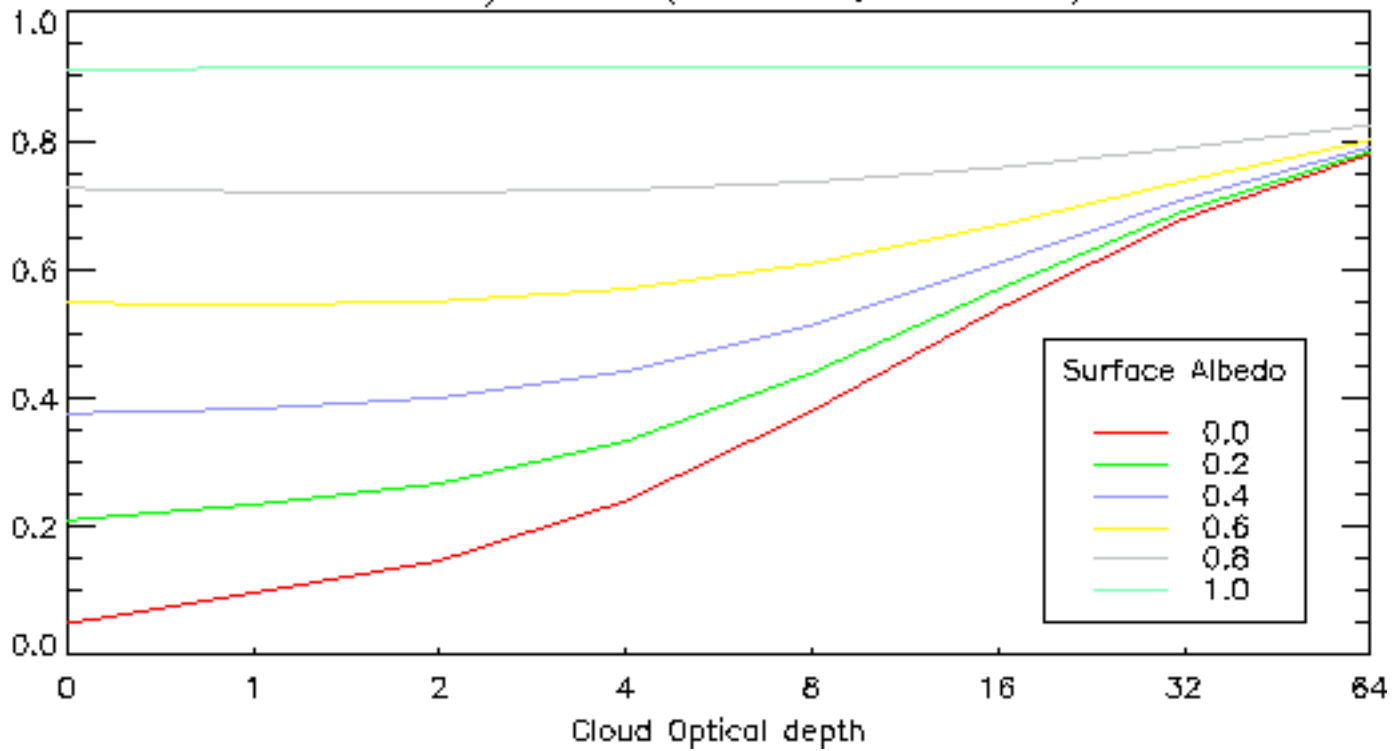
```
#!/local/gnu/bin/bash
#####
# shell script for Example 2
# vary optical depth and surface albedo
#####
```

#

```
rm -f sbchk.2
```

```
for albcon in 0 .2 .4 .6 .8 1      ; do
for tcloud in 0 1 2 4 8 16 32 64 ; do
echo "
  &INPUT
  tcloud=$tcloud
  albcon=$albcon
  idatm=4
  isat=0
  wlinf=.55
  wlsup=.55
  isalb=0
  iout=10
  sza=30
/" > INPUT
sbdart >> sbchk.2
done
done
```

This shell script writes out a new version of INPUT for each iteration of the nested for loops. Results for this run are shown below. Note: when reading the output from this run into your graphics software remember that the inner loop represents variations in cloud optical depth.

Monochromatic Surface Irradiance ($\lambda = 0.55$, SZA = 30)Planetary Albedo ($\lambda = 0.55$, SZA = 30)**Example 3.**

Compute the spectral surface irradiance in the thermal IR for three cases: clear skies, and high altitude clouds of optical depth 1 and 5.

Method: Similar to example 1, but wavelength range has been changed to 4-20 μm . Here is a shell script which performs the required calculations:

```
#!/local/gnu/bin/bash
#####
# shell script for Example 3
# spectral output in thermal IR
#####

rm -f sbchk.3

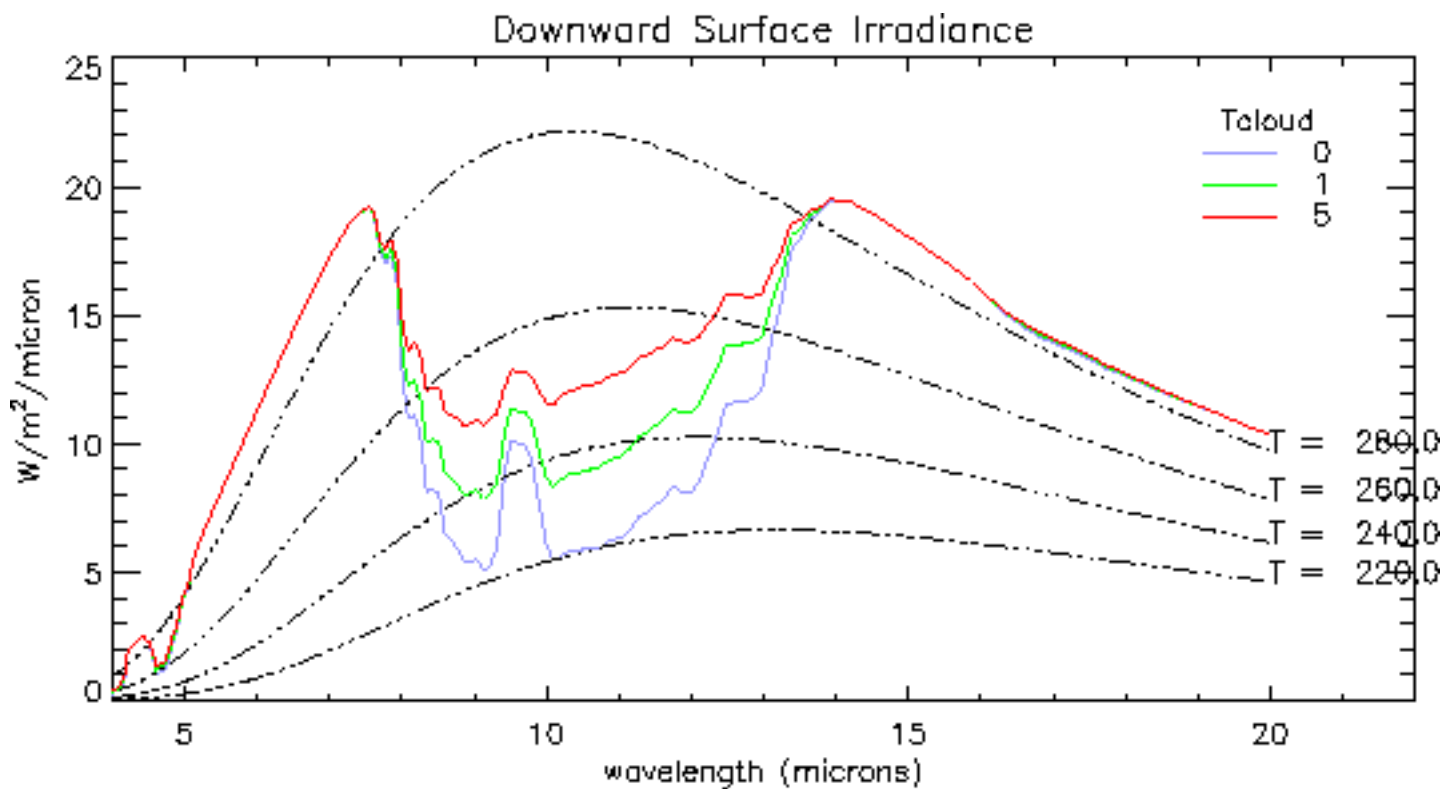
for tcloud in 0 1 5 ; do

echo "
&INPUT
  tcloud=${tcloud}
  zcloud=8
  nre=10
  idatm=4
  sza=95
  wlinf=4
  wlsup=20
  wlinc=-.01
  iout=1
/" > INPUT

sbdart >> sbchk.3

done
```

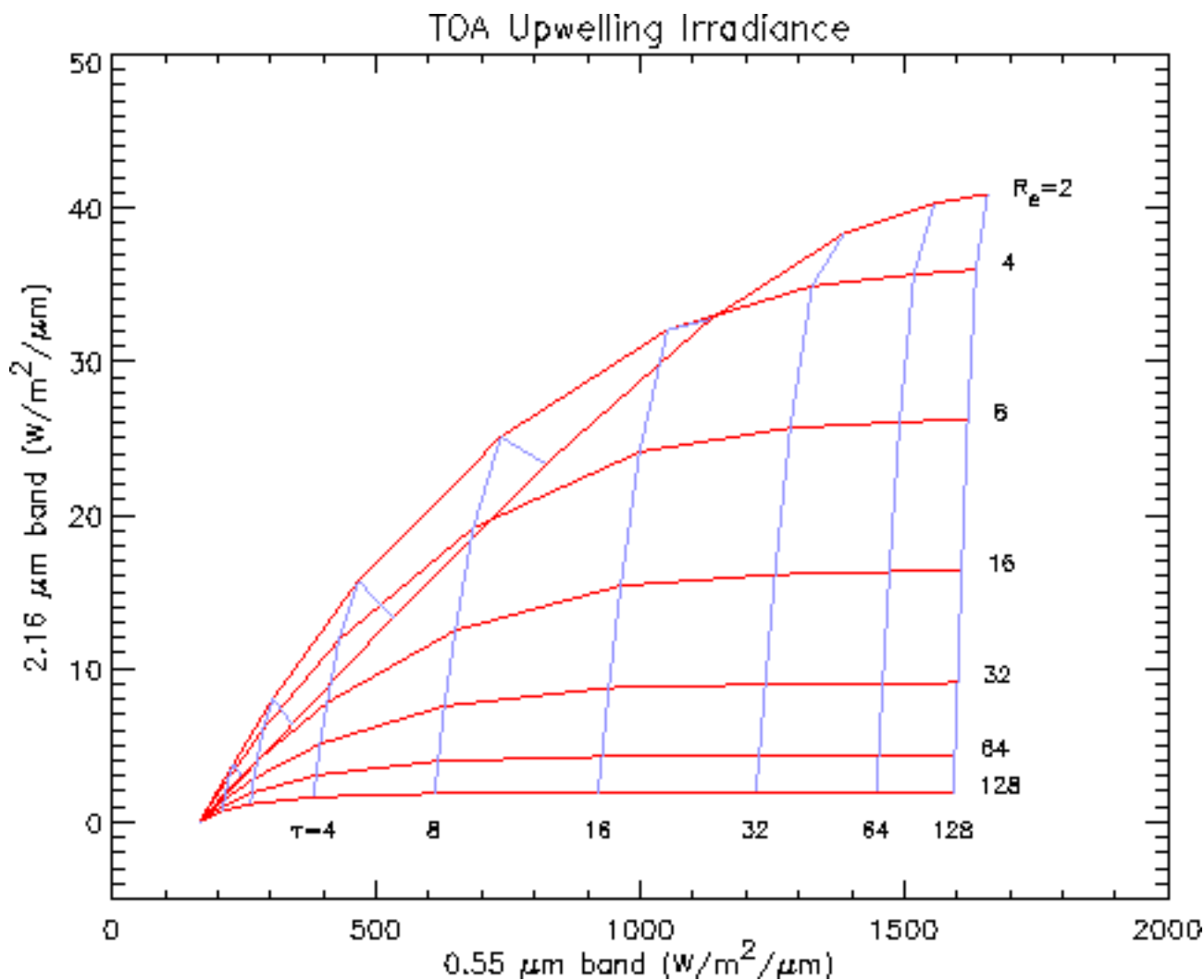
The output for this run is shown here:



Example 4.

Use SBDART to illustrate the Nakajima and King (1990) method for retrieving cloud optical depth and cloud drop effective radius from measurements in two pass bands: 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.

Method: Plot the radiance at $0.55 \mu m$ (non-absorptive band) on the vertical axis and radiance at $2.16 \mu m$ (absorptive band) on the horizontal axis. Compute the TOA upwelling flux in these two bands for cloud optical depths = 0,1,2,4,8,16,32,64 and for cloud drop effective radius = 2,4,8,16,32,64,128. You can compute this example by running the bash script, `sbcmd.4`, which is included in the SBDART distribution package. Compare your results to those shown here:



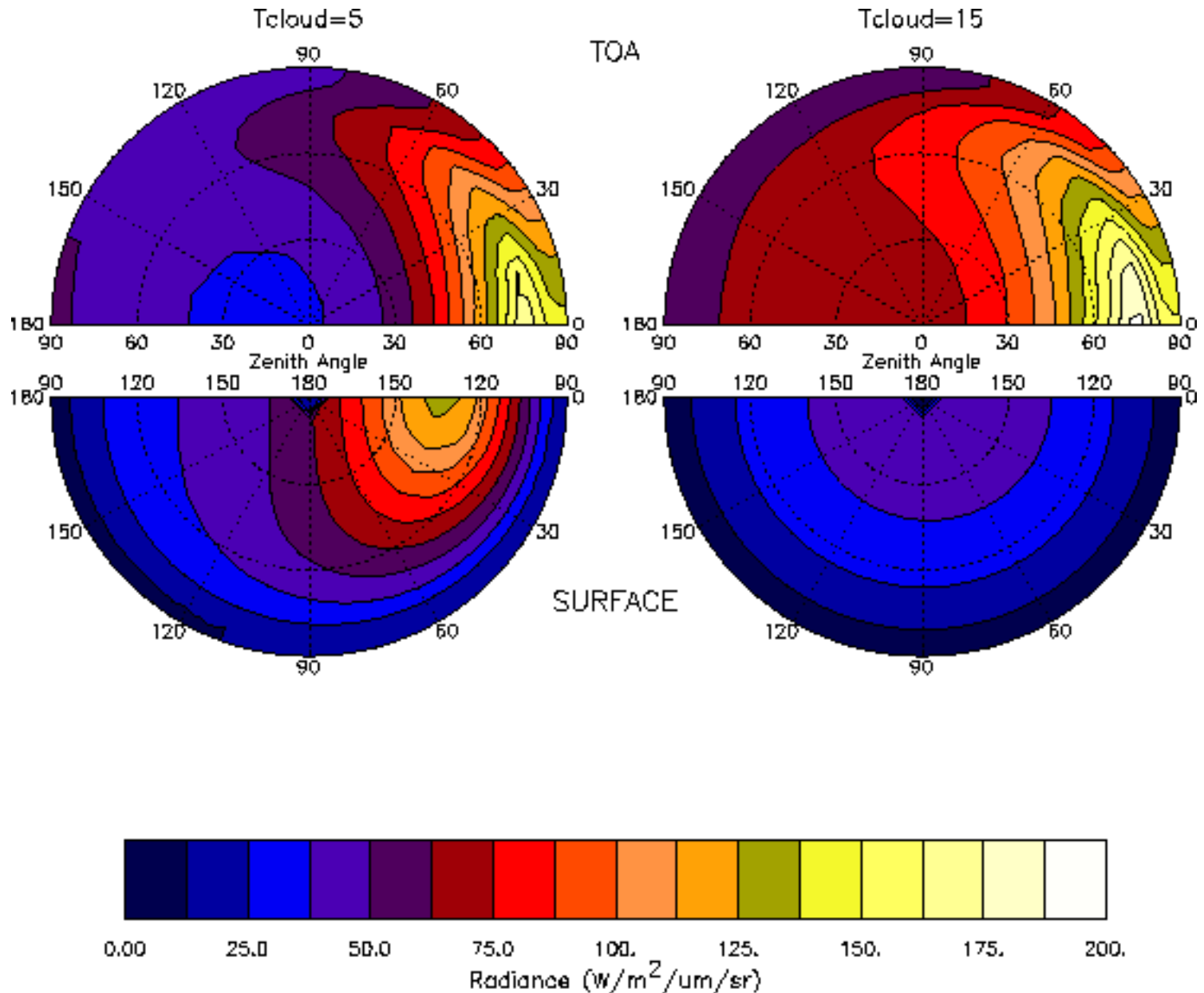
Example 5.

Compute the radiance above and below 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 clouds of optical depth 5 and 15. This example can be executed with script sbcmd.5.

Radiance information is obtained by specifying IOUT=20, 21, or 23, and by setting values for UZEN and PHI, which are the zenith angles and relative azimuth angles at which the radiance information is generated ([Radiance Viewing Geometry](#)). 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=23 output format provides the same irradiance information as produced by examples 2, 3 or 4 and is supplemented by the radiance output quantities. The output for

IOUT=20 and 21 provides the radiance at the surface, and at the top-of-the-atmosphere (TOA), respectively. The IOUT=23 format is a combination of these two output options, providing the upwelling radiance (zenith < 90) at the TOA, and the downwelling (zenith > 90) radiance at the surface. The definitions of the viewing geometry and other radiance inputs are fully described in the [rt.doc](#) online document. Below we show contour plots of the radiance in the upper hemisphere as a function of zenith angle and relative azimuth angle. The contours in the upper semicircle represent TOA radiance values, while the lower semicircle shows surface radiance. The optical depth 5 case is on the left.



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