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Tools for Atmospheric Radiative Transfer: *Streamer* and *FluxNet*

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Abstract---Two tools for the solution of radiative transfer problems are presented. *Streamer* is a highly flexible medium spectral resolution radiative transfer model based on the plane-parallel theory of radiative transfer. Capable of computing either fluxes or radiances, it is suitable for studying radiative processes at the surface or within the atmosphere and for the development of remote-sensing algorithms. *FluxNet* is a fast neural network-based implementation of *Streamer* for computing surface fluxes. It allows for a sophisticated treatment of radiative processes in the analysis of large data sets and potential integration into geophysical models where computational efficiency is an issue. Documentation and tools for the development of alternative versions of *FluxNet* are available. Collectively, *Streamer* and *FluxNet* solve a wide variety of problems related to radiative transfer: *Streamer* provides the detail and sophistication needed to perform basic research on most aspects of complex radiative processes while the efficiency and simplicity of *FluxNet* make it ideal for operational use.

Keywords: Radiative transfer models, atmospheric processes, radiation budget, satellites.

INTRODUCTION

The transfer of solar (shortwave) and terrestrial (longwave) radiation through the atmosphere influences all aspects of the climate system. For a significant portion of the earth's surface the radiation budget is the dominant term in the surface energy balance. Understanding how radiation is attenuated by clouds, aerosols, and gases as it passes through the atmosphere is therefore a prerequisite to understanding the dynamic and thermodynamic components of the global climate system. For example, the radiative effect of clouds influences heating and cooling within the atmosphere, which in turn influence the vertical and horizontal movement of air. But the cloud radiative effect is not the same for all clouds, and depends upon the cloud thickness, particle size distribution, density, and vertical position. Gases also play an important role in radiative transfer. Indeed, the "greenhouse effect", as applied to the earth's atmosphere, is a radiative process summarizing the absorption and emission of terrestrial radiation by gases such as carbon dioxide, water vapor, and methane.

In this paper two general purpose tools for solving atmospheric radiative transfer problems are described. The first, *Streamer*, is a medium spectral resolution model suitable for studying the radiation budgets at the surface and within the atmosphere. It can also be used to simulate satellite sensor observations. The second tool, *FluxNet*, is a neural network-based radiative transfer model trained on *Streamer* calculations, but is limited to the calculation of radiative fluxes at the surface. Its advantage is that it is extremely fast. This is important for processing large data sets or including sophisticated radiative transfer calculations in complex geophysical models. Each of these tools is designed to provide solutions to a wide array of radiative transfer problems.

A variety of other radiative transfer models exist, both for the calculation of radiative fluxes and the simulation of radiances measured by satellite sensors. However, those used for the calculation of radiative fluxes are generally components of climate models (cf., Ellingson, Ellis, and Fels, 1991) and are not well documented or easy to use. For this reason they will not be discussed further in this paper. Radiative transfer models that are well documented, reliable, and available to the scientific community include LOWTRAN (Kneizys and others, 1988), MODTRAN (Snell and others, 1995), and 6S (Vermote and others, 1994). While there are others, these three have been widely used in remote sensing applications. They are all medium or high spectral resolution band models and incorporate thorough treatments of gas absorption (Table 1). However, the cloud models in LOWTRAN/MODTRAN are not easily modified, and the two-stream approximation for multiple scattering results in significant errors under certain conditions. Additionally, none of these models computes fluxes directly, and the user interfaces for LOWTRAN and MODTRAN are somewhat crude. The 6S model is commonly used for atmospheric corrections, but it is limited to the shortwave and does not include clouds.

Streamer and *FluxNet* were developed to address some of these shortcomings for applications involving the assimilation of satellite-derived information into atmosphere-ice-ocean models. Requirements included the ability to simulate satellite radiances for algorithm development, incorporate a sophisticated treatment of radiative processes in a coupled ice-ocean model, and generate large satellite-derived forcing fields. A flexible interface to specify cloud and surface optical properties not commonly found in other radiative transfer models was important in the development of these two tools. Although both have their origin in polar research, they have been extended and applied to global problems.

STREAMER

Streamer is a general purpose atmospheric radiative transfer model that computes either radiances (intensities) or irradiances (fluxes) for a wide variety of atmospheric and surface conditions. Its user interface is extremely flexible and easy to use. *Streamer*'s major features are:

1. Radiances for any polar and azimuthal angles, shortwave and longwave fluxes, net fluxes, cloud radiative effect ("cloud forcing"), and heating rates can be computed at any atmospheric level.
2. Both two-stream and discrete ordinates solvers are included.
3. Gas absorption and clouds are parameterized for 24 shortwave and 105 longwave bands.
4. Built-in atmospheric data include water and ice cloud optical properties, five aerosol optical models, four aerosol vertical profiles, and seven standard atmospheric profiles. Either standard or user-defined profiles can be used, or total column amounts of water vapor, ozone, and aerosols can be specified.
5. Each computation is done for a "scene", where the scene can be a mixture of up to 10 cloud types occurring individually, up to 10 overlapping cloud sets of up to 10 clouds each, and clear sky, all over some combination of up to three surface types.
6. Spectral albedo data for open ocean (sea water), meltponds, bare ice, snow, green vegetation, and dry sand are included.
7. The user interface provides looping structures for up to ten variables at a time; variables can be reassigned, and output can be easily customized.

Processing is controlled by a set of options and input data. The options define the characteristics common to all the data, while the data provides information for each scene or case (e.g., a pixel or observation in time). Output includes surface and top of the atmosphere (TOA) radiative fluxes, surface albedo, and cloud radiative effect for flux calculations, or radiances and TOA albedo or brightness temperature. Either of two files may be written: one with labeled results or one that is user-customizable.

Components

Two radiative transfer solvers are used in *Streamer*: a two-stream method and a discrete ordinate solver. The discrete ordinate radiative transfer (DISORT) solver is described in Stamnes and others (1988) and has been available to the public as a stand-alone package for many years. The two-stream method is described in Toon, McKay, and Ackerman (1989). It uses a Delta-Eddington approximation for the shortwave and a hemispheric means approximation for the longwave portion of the spectrum. The discrete ordinate solver is the more accurate of two, and can be used to compute either radiances or fluxes. The two-stream solver computes only fluxes but is much faster than DISORT. Differences in fluxes computed using the two methods are generally small, but can be significant under certain circumstances. For example, two-stream results for longwave fluxes are within 0.5 W m^{-2} of the 24-stream discrete ordinates values. In the shortwave, differences depend on the surface albedo and the illumination geometry. The two- and 24-stream fluxes are within about 1% for a dark surface and a high sun, but at the other extreme, differences are as high as 10% with a large solar zenith angle and/or a bright surface.

Cloud optical properties are based on parameterization schemes from three different sources. For water clouds, the data are taken from Hu and Stamnes (1993). Effective radii, the ratio of the third to the second moments of the particle size distribution, range from 2.5 to 60 microns and are given for 293 wavelengths throughout the shortwave and longwave portions of the spectrum. For ice clouds in the shortwave, the five-band parameterization of Ebert and Curry (1992), based on randomly oriented hexagonal cylinders, is used. Longwave ice cloud optical properties are based on Mie calculations using spherical particles for 132 wavelengths. This parameterization is unpublished but follows the methodology of Hu and Stamnes. Of course, using spherical particles in the determination of ice cloud optical properties may not be realistic, since ice crystals may take on a variety of shapes (cf, Takano and Liou, 1989; Schmidt and others, 1995). However, no parameterization using other shapes (e.g., hexagons) across the entire longwave range is currently available. Both the water and ice cloud parameterizations of optical properties are based on the empirical relationship between the particle effective radius and extinction, single scatter albedo, the asymmetry parameter, and the cloud water content. For radiative transfer calculations, water cloud and longwave ice cloud optical properties are averaged over *Streamer* spectral bands.

Aerosol amounts as extinction coefficients can be distributed vertically according to a user-supplied profile or one of the internal standard profiles. Four vertical profile shapes are available that are combinations of two tropospheric and two stratospheric loadings, based on data in the LOWTRAN-7 radiative transfer model (Kneizys and others, 1988). Tropospheric background, rural, urban, maritime (Shettle and Fenn, 1979) and Arctic haze (Blanchet and List, 1983) aerosol optical property models are available. Standard temperature and humidity profiles include tropical, mid-latitude, subarctic, and arctic. They are based on data in Ellingson, Ellis, and Fels (1991) except for the Arctic profiles of temperature and humidity, which are derived from Arctic Ocean coastal and drifting station data. Gaseous absorption is parameterized using an exponential sum fitting technique (Wiscombe and Evans, 1977) with coefficients provided by S.-C. Tsay (personal communication, 1991; cf., Tsay, Stamnes, and Jayaweera, 1989). Only four gases are present in *Streamer*: water vapor, carbon dioxide, ozone, and oxygen.

Several spectral albedo data sets are available in *Streamer*. Sand and vegetation data are from Vermott and others (1994); meltpond and bare ice albedos are from Grenfell and Maykut (1977); sea water data are based on Brieglieb and others (1986); freshwater albedos are from Fresnel calculations; and snow spectral albedos were computed using a four-stream model based on the ideas of Warren and Wiscombe (1980). Surface bi-directional reflectance functions can not currently be employed.

Streamer includes band weights to approximate the sensor spectral response functions of the Advanced Very High Resolution Radiometer (AVHRR) on-board the NOAA polar orbiting satellites, the Along Track Scanning Radiometer (ATSR) on ERS-1, the High Resolution Infrared Radiation Sounder (HIRS/2) of the Tiros Operational Vertical Sounder (TOVS) on NOAA polar orbiters, and the Moderate Resolution Imaging Spectroradiometer (MODIS), a future NASA instrument. However, with only 24 shortwave bands and longwave bands of 20 cm^{-1} width, satellite applications are limited to the broader band sensors. For example, the longwave channels of the AVHRR and the ATSR span as many as six *Streamer* spectral bands but the shortwave channels cover as few as one. There are a few HIRS and MODIS channel pairs that are completely contained within the same *Streamer* spectral band, so no distinction between them is possible. For other sensors, the user can specify band weights and central wavenumbers.

Running Streamer

Streamer can be run in two modes. The stand-alone mode allows the solution of radiative transfer problems with input and output specified from one or more files. This mode is ideal for asking questions related to radiative transfer such as satellite algorithm development or sensitivity studies. In the second, *Streamer* is called as a Fortran subroutine. This mode allows *Streamer* to be integrated into models or data processing systems.

To run *Streamer* as a stand-alone model a file containing a sequence of commands and data is used. The command set includes: $OPTIONS, $SETDATA, $CASE, $REPLACE,

$EXCHANGE, $PRINT, and $COMMENT. The $OPTIONS command indicates that a block of options containing variables common to all cases (or "scenes") should be read. The $SETDATA and $CASE commands signify that data for a new case are to be read. The $REPLACE and $EXCHANGE commands are used to assign or reassign variable values from the previous scene's data, and can be used to initiate loops. Specific variables can be printed for each case without having to modify the source code by using $PRINT. Comments can be added to the input file with $COMMENT or simply with ";".

The input data types are very flexible (Table 2). For example, if the solar zenith angle is not specified then it will be computed; the surface albedo specification can be broadband, visible band, or multiband; cloud thickness can be specified as optical thickness, thickness in pressure or height units; water vapor, aerosol, and ozone profiles can be provided or total column amounts can be specified. When less detail than needed is provided, built-in data are used.

With $REPLACE and $EXCHANGE scalar variables can be assigned new values, as can individual array elements or entire arrays. These commands also provide the facility for doing calculations over a range of variable values. Two looping structures are available, one where the starting, ending, and increment values are specified as in most high-level programming languages, and another where all values to be evaluated are specified. If more than one loop is specified, they are nested. As an example, the following statement reassigns the solar zenith angle and loops over a range of cloud particle effective radii from 2 to 10 microns in increments of 1 micron, and loops over a list of five cloud optical thicknesses for each effective radius.

```
$replace zen=65.0; cldre(1)=(2, 10., 1.); cldthick(1)=[0.1, 2, 4, 8]
```

Default output includes descriptive text and values for surface and top of the atmosphere radiative fluxes, surface albedo, and cloud radiative effect for flux calculations, or radiances and TOA albedo or brightness temperatures (Table 3). The $PRINT command can be used to select only those parameter values of interest with or without the descriptive text. For example, the following statement prints some descriptive text and just a few variable values on two separate lines:

```
$print 'bstart, bend: ', bstart, bend, /NEWLINE, \
' Re, albedo, zenith angle: ', cldre, satalb(1,2), zen
```

This statement is specified once but will be applied to every case in the input file.

While the user interface with $REPLACE and $PRINT provides tremendous flexibility and control, there may be applications where *Streamer* needs to be integrated into existing Fortran code. For example, simple parameterizations of radiative fluxes currently used in sea ice models could be replaced with a radiative transfer model. In applications such as this, *Streamer* is available as a subroutine, where all basic data normally given in the input file are passed in as a list of arguments to the subroutine. Output data are passed back to the calling routine.

Sample Applications

Figure 1-3 provide a few examples of how *Streamer* has been used. Figure 1 gives downwelling shortwave and longwave fluxes as a function of cloud physical thickness and cloud fractional coverage in the scene. These data were generated using the looping structures in the $REPLACE command. Figure 2 shows top of the atmosphere brightness temperatures and brightness temperature differences for the 11 and 12 μm channels of the AVHRR over a range of cloud optical depths and droplet effective radii for a specific set of viewing, atmospheric, and surface conditions. This type of data can be used for the retrieval of cloud effective radius and optical depth from AVHRR observations. Figure 3 shows downwelling longwave fluxes over the Arctic that were computed using cloud and atmospheric parameters derived from the TOVS.

FLUXNET

FluxNet is an artificial neural network implementation of the two-stream radiative transfer solution for surface fluxes in *Streamer*. Artificial neural networks have been applied to tasks involving the analysis of complex patterns such as signal processing, optical character recognition, and even stock market forecasting. Although a variety of architectures have been created, the three- and four-layer backpropagation networks are the most popular. The signals from the input units are fed forward through processing nodes in the hidden layers to the output units. The output is then compared to desired results, the error is propagated backwards from the output layer through the hidden layers, and the weight of each connection is adjusted accordingly. Characteristics of neural networks that make them attractive are: (1) the four-layer network can, theoretically, determine any computable function, (2) no assumptions about the statistical distribution of input variables are made, and (3) they are very fast once they are trained. However, since neural network-based estimation methods do not include any assumptions about the underlying non-linear physics, estimates can only be truly optimal with respect to the training data set and estimation errors need to be determined through the application to an independent test or validation data set.

FluxNet was trained with surface radiative fluxes computed by *Streamer.* Ten thousand cases encompassing a wide range of global surface and atmospheric conditions were used in the training. There four outputs are downwelling and upwelling, shortwave and longwave fluxes at the surface. The input variables to *FluxNet* constitute a subset of those required for *Streamer*, as listed in Table 4. Two versions of the network are currently available: one requiring temperature and humidity profiles in the input stream and one using the total column water vapor rather than the profiles. The code is very small and extremely fast. C and IDL (Interactive Data Language from Research Systems Inc., Boulder, Colorado) programming language versions are available. Detailed instructions and tools for creating custom networks are given in the software documentation.

FluxNet is a much simpler model than *Streamer.* Its principle advantage is that it is faster by two to four orders of magnitude (100 to 10,000 times), making it ideal for large jobs like image processing, which consist of thousands to millions of different cases. Users of *Streamer* should be aware of the following limitations in *FluxNet*:

1. Each scene can consist of just one surface type and one cloud layer.
2. The 24 shortwave and 105 longwave spectral bands in *Streamer* have been consolidated into one shortwave and one longwave band; i.e., only broadband calculations are done.
3. Input and output data types, ordering, and units are fixed. there are no options and no command language.

A comparison between *FluxNet* and *Streamer* downwelling fluxes for 5000 test cases is shown in Figure 4. The biases (mean differences) are very close to zero, and the root-mean-square errors are 2-3% of the mean flux values. Additionally, 90% of the errors are 5% or less, which is within the accuracy (3-5%) of radiometers commonly used in the field. However, for shortwave fluxes less than about 20 W m^{-2}, errors can be up to 30%. Upwelling fluxes (not shown) have smaller root-mean-square errors.

SUMMARY

Streamer and *FluxNet* are tools for the solution of a wide variety of radiative transfer problems. *Streamer* is a highly flexible and customizable general purpose radiative transfer model. It allows for the computation of both irradiances and radiances and is therefore suitable for the simulation of some satellite signals and the study of radiative heat budgets in the atmosphere or at the surface. Weighting functions for a number of satellite sensors are provided. Users can select from a wide range of built-in atmospheric profiles and surface types. Specification of cloud properties is in terms of effective particle size, water content, physical or optical thickness, and vertical position. *Streamer* can be run in a stand-alone mode or called as a subroutine. *FluxNet* provides a computationally efficient method for a sophisticated treatment of radiative transfer processes and is therefore suitable for the processing of large data sets or incorporation within models. *FluxNet* is 100 to 10,000 times faster than *Streamer.* For instantaneous observations, differences (root-mean-square errors) between *Streamer* and *FluxNet* are on the order of 11 W m^{-2} for downwelling shortwave fluxes and 7 W m^{-2} for downwelling longwave fluxes without significant biases. Assuming daily sampling for monthly average calculations these errors are reduced by a factor of five (square root of 30; cf., Key, Schweiger, and Stone, 1997), which is well within the requirements of 10 W m^{-2} for monthly surface fluxes (WMO, 1987).

Streamer is implemented in Fortran 77 and has been compiled and tested on Intel, Sun, SGI, HP, IBM, and DEC platforms. Ports to other platforms should be straightforward. *FluxNet* is available in ANSI C and IDL (Interactive Data Language) and has been tested on Intel and Sun platforms. Detailed instructions for creating custom networks are given in the documentation. *Streamer* and *FluxNet* may be obtained by anonymous ftp from stratus.bu.edu or through the World Wide Web at http://stratus.bu.edu. Source code, user guides, and test input/output data are provided.

Acknowledgments---*Streamer* has its roots in the program *strats* by S-C. Tsay. Much of the *strats* code was used in the original version of *Streamer* (c. 1992) and some components remain an integral part of the model. The two-stream solution is based on code from T. Ackerman. Thanks to R. Stone for many valuable discussions and for assistance in the ice cloud Mie calculations. The *Stuttgart Neural Network Simulator* by Andreas Zell and others (http://www.informatik.uni-stuttgart.de/ipvr/bv/projekte/snns/snns.html) was used in the development of *FluxNet.* Funding was provided primarily by the NASA EOS interdisciplinary project POLES (NAGW-

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FIGURE CAPTIONS

Figure 1. Downwelling shortwave and longwave fluxes at the surface as a function of cloud fraction f and physical thickness Δz.

Figure 2. Brightness temperatures and temperature differences in two infrared window channels as a function of cloud optical depth τ and droplet effective radius Re.

Figure 3. Downwelling longwave fluxes (W m^{-2}) at the surface computed using TOVS-derived profiles and cloud properties. (Courtesy of J. Francis)

Figure 4. Comparison of *FluxNet* and *Streamer* downwelling shortwave fluxes (top) and downwelling longwave fluxes (bottom), both at the surface. Bias is the mean difference between the two (*FluxNet* minus *Streamer* flux); RMSE is root-mean-square error.

Table 1.

	LOWTRAN	MODTRAN	6S	*Streamer*
Numerical approximation method	Two-stream, including atmospheric refraction	Two-stream, including atmospheric refraction; discrete ordinates also in MODTRAN-3	Successive orders of scattering	Discrete ordinates and two-stream
Spectral resolution	20 cm^{-1}	2 cm^{-1}	10 cm^{-1}, shortwave only	24 shortwave bands; 20 cm^{-1} bandwidth in longwave
Clouds	Eight cloud models	Eight cloud models	No clouds	Flexible specification of cloud optical and physical properties
Aerosols	Four optical models	Four optical models	Six optical models	Five optical models
Gas absorption*	Principle and trace gases	Principle and trace gases	Principle and trace gases	Principle gases only
Atmospheric profiles	Standard and user-specified	Standard and user-specified	Standard and user-specified	Standard plus Arctic and user-specified
Surface characteristics	Lambertian, no built-in models	Lambertian, no built-in models	Lambertian spectral albedo models built-in; Bi-directionally reflecting surface possible	Lambertian, built-in spectral albedo models
Primary output parameter	Radiance	Radiance	Radiance/reflectance	Radiance/reflectance/ brightness temperature or flux
User interface	Formatted input file	Formatted input file	Input file	Input file with command language

*In this table, principle gases are H_2O, O_3, CO_2, and O_2. Trace gases include, among others, CH_4, N_2O, and CO.

Table 2.

Category	Variable Type
Options	Fluxes or radiances? Number of streams, shortwave and longwave Gaseous absorption? Rayleigh scattering? Surface albedo and emissivity type Standard temperature and humidity profile type Aerosol profile shape and optical model Units selection Band weight file name Output file name
Location, viewing geometry, bands	Year, month, day, hour, latitude, longitude or solar zenith angle Viewing angles Starting and ending spectral bands or channel
Surface Characteristics	Albedo, surface types and fractions Temperature and emissivity
Cloud Characteristics	Optical or physical thickness, top or bottom temperature Height, particle effective radius, phase, fraction Overlapping sets
Profiles	Profile input options, profiles or column amounts

Table 3.

Category	Variable Type
Header Information	Repeat of input options
Profiles	Height, pressure, temperature, water vapor density, relative humidity, ozone, and aerosol extinction, total column amounts
Cloud Characteristics	Physical thickness, pressure thickness, optical thickness, fraction, top temperature, top pressure and height, effective radius, liquid/ice water content, phase, overlap sets
Surface Characteristics	Clear sky fraction, fraction of each surface type, input surface albedo at 0.6 μm, surface temperature, broadband surface albedo
Fluxes	Downwelling direct, diffuse, and total shortwave, downwelling longwave, upwelling shortwave and longwave, net irradiances, heating/cooling rates, cloud radiative effect
Radiances	Spectrally integrated for each polar angle, azimuthal angle, and level; top level albedo and/or brightness temperature

Table 4:

Category	Variable Type
Geometry	Solar zenith angle
Surface Characteristics	Broadband albedo Temperature and emissivity
Cloud Characteristics	Phase, particle effective radius, water content Optical depth, top pressure, fraction
Atmosphere	Aerosol optical depth, total column ozone Total column water amount or temperature and humidity profiles

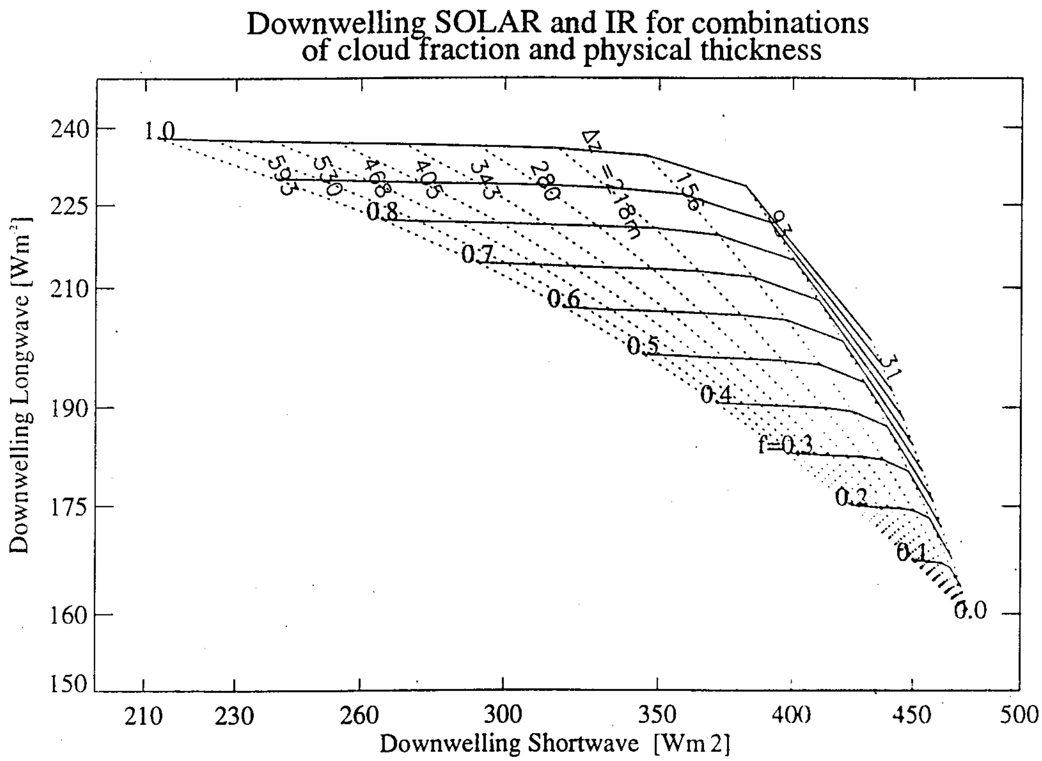

Figure 1. Downwelling shortwave and longwave fluxes at the surface as a function of cloud fraction f and physical thickness Δz.

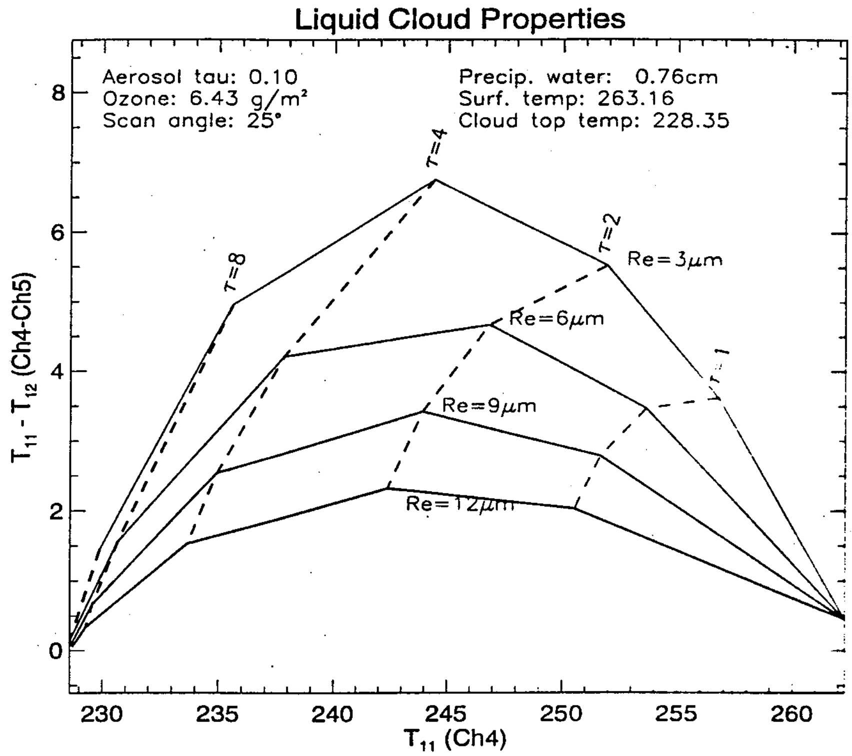

Figure 2. Brightness temperatures and temperature differences in two infrared window channels as a function of cloud optical depth τ and droplet effective radius Re.

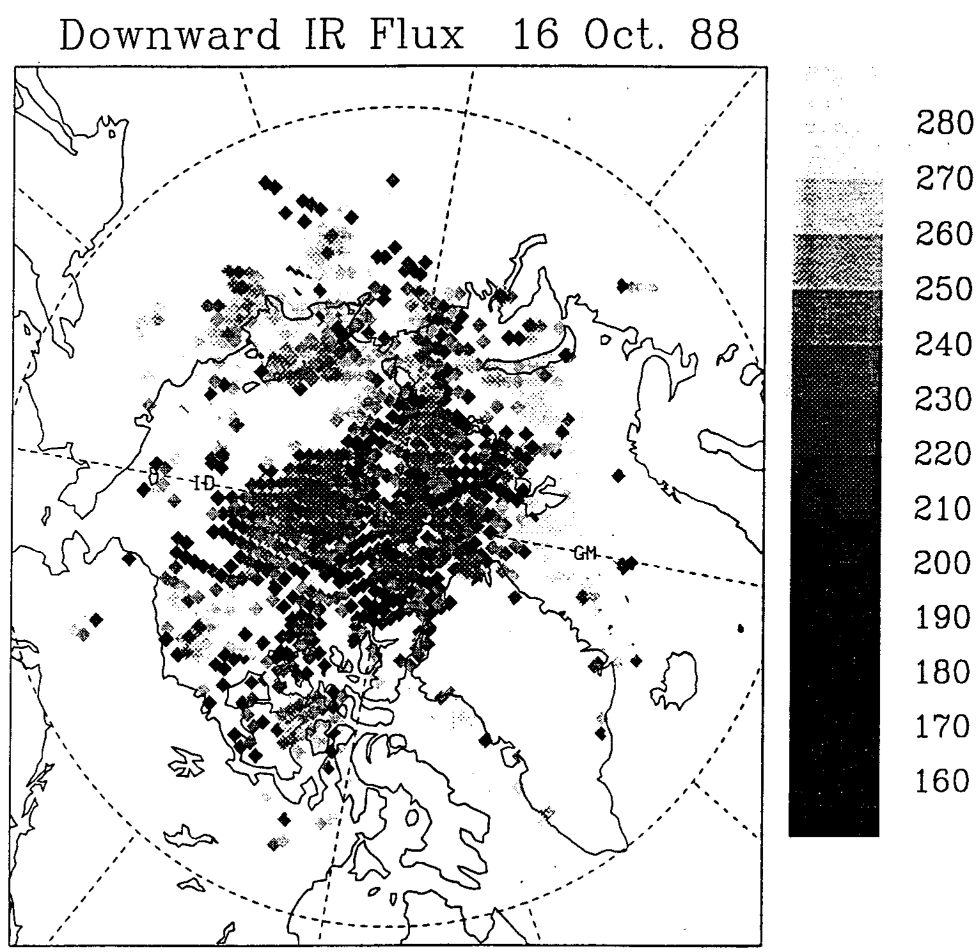

Figure 3. Downwelling longwave fluxes (W m^{-2}) at the surface computed using TOVS-derived profiles and cloud properties. (Courtesy of J. Francis)

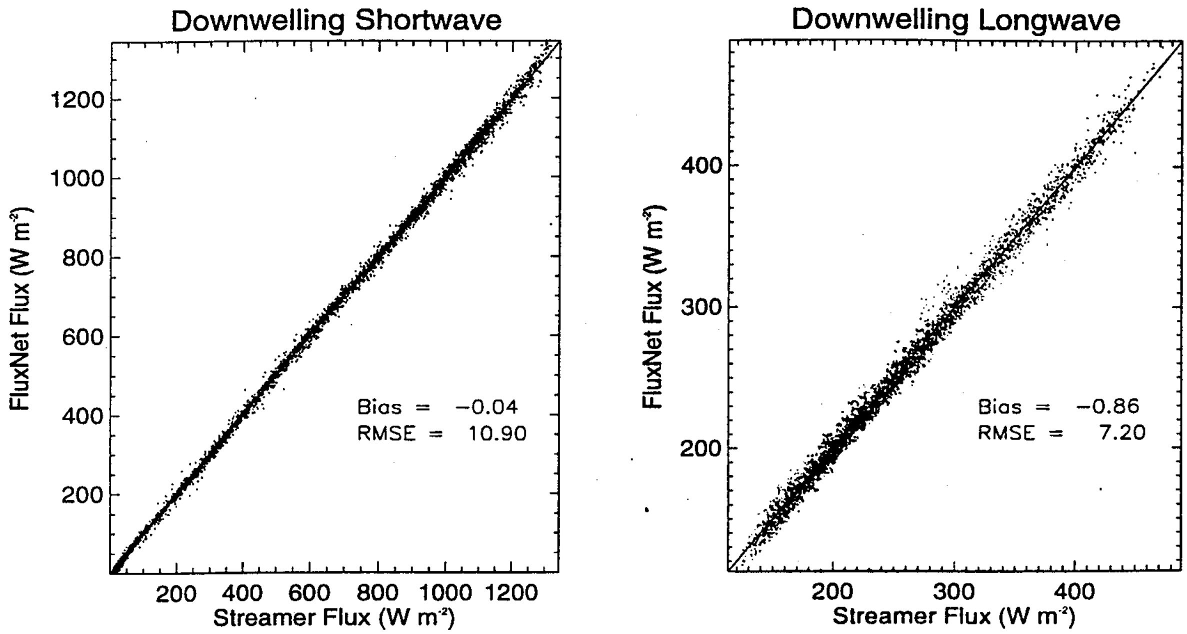

Figure 4. Comparison of *FluxNet* and *Streamer* downwelling shortwave fluxes (top) and downwelling longwave fluxes (bottom), both at the surface. Bias is the mean difference between the two (*FluxNet* minus *Streamer* flux); RMSE is root-mean-square error.