

# 3D Radiative Transfer in Cloudy Atmospheres



*The Noble Cumulus*  
oil and acrylic on canvas 22×28 in.

A. Marshak A.B. Davis  
Editors

# 3D Radiative Transfer in Cloudy Atmospheres

With 227 Figures

 Springer

Alexander Marshak

NASA/Goddard Space Flight Center  
Climate and Radiation Branch  
Mail Code 913  
Greenbelt, Maryland 20771  
USA

Anthony Davis

Los Alamos National Laboratory  
Space and Remote Sensing Sciences Group  
(ISR-2)  
Los Alamos, New Mexico 87545  
USA

---

### About the painting

It was Ruskin, a noted art critic of the 19th century, who commented on the appearance of clouds in art and recollected that 'There has been so much . . . fog and artificial gloom, besides, that I find it is actually some two years since I last saw a noble cumulus under full light'. The painting 'The Noble Cumulus' is inspired by the nobility of illuminated clouds and their effects on radiation, the principal topic of this book. This painting is one of a series that is inspired by the artist's interest in the science of clouds and the role the study of clouds has played in the development of meteorology as a science over the years. This topic and others are described in the article by the artist: The useful pursuit of shadows. *Am. Scientist*, 91, 442–449 (2003). Other art and a pdf of this article can be found at <http://cloudsat.atmos.colostate.edu/CSMart.php>.

### About the artist

Graeme L. Stephens is a Professor in the Department of Atmospheric Sciences at Colorado State University in Ft. Collins, Colorado. He has spent much of his career studying clouds and their effects on atmospheric radiation, has numerous publications, author of a text book on remote sensing and is a contributing author of this book. Professor Stephens has received a number of major awards for his scientific research on clouds and radiation.

---

**Cover image:** 3D Monte Carlo simulation of the solar radiance field from a broken cumulus field itself simulated using a high-resolution dynamical cloud model (Fig. 4.6 in the text).

---

Library of Congress Control Number: 2005925575

ISSN: 1610-1677

ISBN-10 3-540-23958-8 Springer Berlin Heidelberg New York

ISBN-13 978-3-540-23958-1 Springer Berlin Heidelberg New York

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable for prosecution under the German Copyright Law.

Springer is a part of Springer Science+Business Media  
springeronline.com  
© Springer-Verlag Berlin Heidelberg 2005  
Printed in The Netherlands

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Typesetting: by the authors and TechBooks using a Springer L<sup>A</sup>T<sub>E</sub>X macro package

Cover design: Erich Kirchner

Printed on acid-free paper SPIN: 10820397 54/3141/jvg 5 4 3 2 1 0

---

## Dedication

To the memory of

Georgii A. Titov

(March 5, 1948 – July 25, 1998)

and

Gerald C. Pomraning

(February 25, 1936 – February 6, 1999)



George Titov and Jerry Pomraning (courtesy of Lucia Levermore).

“[Preliminary] Monte Carlo results are generally modulo a factor of  $\pi$ .”

Georgii Titov

“Life is an integral!”

Jerry Pomraning

# Physics of Earth and Space Environments

[springeronline.com/series/5117/](http://springeronline.com/series/5117/)

---

The series *Physics of Earth and Space Environments* is devoted to monograph texts dealing with all aspects of atmospheric, hydrospheric and space science research and advanced teaching. The presentations will be both qualitative as well as quantitative, with strong emphasis on the underlying (geo)physical sciences.

Of particular interest are

- contributions which relate fundamental research in the aforementioned fields to present and developing environmental issues viewed broadly
- concise accounts of newly emerging important topics that are embedded in a broader framework in order to provide quick but readable access of new material to a larger audience

The books forming this collection will be of importance for graduate students and active researchers alike.

## Series Editors:

Rodolfo Guzzi  
Responsabile di Scienze della Terra  
Head of Earth Sciences  
Via di Villa Grazioli, 23  
00198 Roma, Italy

Louis J. Lanzerotti  
Bell Laboratories, Lucent Technologies  
700 Mountain Avenue  
Murray Hill, NJ 07974, USA

Dieter Imboden  
ETH Zürich  
ETH Zentrum  
8092 Zürich, Switzerland

Ulrich Platt  
Ruprecht-Karls-Universität Heidelberg  
Institut für Umweltphysik  
Im Neuenheimer Feld 366  
69120 Heidelberg, Germany

---

## Preface

A few years ago one of us (AM) was giving a series of lectures on three-dimensional (3D) radiative transfer in cloudy atmospheres at the Summer 1999 School “Exploring the Atmosphere by Remote Sensing Techniques” hosted by the Abdus Salam International Centre for Theoretical Physics in Trieste (Italy). By the end of the series, the instructor was asked by students for an available book on the subject. It turned out that in spite of multiple decades of research, relative maturity of the field, the involvement of dozens of scientists worldwide, and hundreds of journal papers, there was in fact no tutorial book in existence. So there was nowhere for students and young researchers to start or to use as a reference. One of the directors of the school, Rodolfo Guzzi, and the editor of the physics section of Springer-Verlag, Christian Caron, who was also there, suggested that we fill this gap by writing a monograph on the subject.

We enthusiastically accepted the Springer-Verlag commission and attracted many leading 3D radiative transfer scientists as co-authors: H. Barker, N. Byrne, R. Cahalan, E. Clothiaux, R. Davies, R. Ellingson, F. Evans, P. Gabriel, A. Heidinger, Y. Knyazikhin, A. Korolev, R. Myneni, I. Polonsky, G. Stephens, E. Takara, and W. Wiscombe. More than half of them are on the science team of the Atmospheric Radiation Measurements (ARM) program sponsored by the U.S. Department of Energy (DOE). A major goal of ARM is to further our understanding of radiative transfer in the atmosphere – especially the role of clouds – and at the Earth’s surface. The DOE’s ARM program has therefore provided generous funding for this book project. We also greatly appreciate the ongoing support we receive from our home institutions, Los Alamos National Laboratory and NASA’s Goddard Space Flight Center, and the support received from the Joint Center for Earth Systems Technology of UMBC, where one of us worked at the beginning of the project. Technical expertise in Springer-Verlag’s LaTeX desktop publishing environment was ensured by Lisa LeBlanc, now with the Canadian CLIVAR Network at McGill University; without her help, we would not have been able to prepare this manuscript.

The title of this book is “Three-Dimensional Radiative Transfer in Cloudy Atmospheres.” At one point, we were tempted to use the more provocative title “*Real* Radiative Transfer in Cloudy Atmospheres.” Indeed, it is the 3D radiative transfer

equation that determines the radiation processes in real cloudy atmospheres. By contrast, the standard 1D model, which can be traced back at least 100 years, is an approximation that should prove useful under certain circumstances. In other words, it is time to think of 3D theory as the golden standard in atmospheric radiative transfer rather than as a perturbation of standard 1D theory.

The book captures and preserves much of the best 3D cloud radiation work done in the last couple of decades, and brings it to better maturity as authors took special care to explain their discoveries and advances to a larger audience. Our primary readership will be made of graduate students and researchers who specialize in atmospheric radiation and cloud remote sensing. However, we hope that remote sensing scientists in other application areas (biosphere, hydrosphere, cryosphere, etc.) will find many portions of the volume stimulating.

Beyond the two introductory chapters, the volume naturally divides into three parts: Fundamentals, Climate, and Remote Sensing. The two last topics are indeed the main concerns in atmospheric radiation science. The chapters are essentially independent but cross-reference each other. We tried our best to avoid overlap; in several places, however, we found it more effective to repeat some material rather than pointing to other portions of the book. Most chapters end with Notes and/or a Suggested Reading list because they open more questions than they answer; these contain input from the authors, the reviewers, and the editors. As much as possible, we tried to use the same notation throughout the whole book. A list of notations and a subject index can be found at the end of the volume. Each chapter has been peer-reviewed by at least one reviewer internal to the author collective and one external reviewer. We wish to thank all reviewers, especially the external ones: Larry Di Girolamo, Qiang Fu, Jeff Haferman, Harshvardhan, Alexei Lyapustin, Andreas Macke, John Martonchik, Lazaros Oreopoulos, Klaus Pfeilsticker, Bill Ridgway, Tamas Várnai, and Tatyana Zhuravleva.

This project took us much longer than we initially anticipated. Being committed to other projects during the daytime, we mostly worked on the book during the evenings and weekends at home, taking time from our families. We are very grateful for their support and understanding. It was rewarding to work on this book, writing our own chapters, reading and editing other chapters. We personally learned a lot and we hope that the readers will enjoy it too.

Finally, we dedicate this book to the memory of two great radiative transfer scientists, G. Pomraning and G. Titov. We consider ourselves lucky to have met them and to have learned so much from them.

Greenbelt, Maryland  
December, 2004

*Alexander Marshak  
Anthony Davis*



---

# Contents

---

## Part I Preliminaries

---

### 1 Scales, Tools and Reminiscences

W.J. Wiscombe ..... 3

### 2 Observing Clouds and Their Optical Properties

E.E. Clothiaux, H.W. Barker and A.V. Korolev ..... 93

---

## Part II Fundamentals

---

### 3 A Primer in 3D Radiative Transfer

A.B. Davis and Y. Knyazikhin ..... 153

### 4 Numerical Methods

K.F. Evans and A. Marshak ..... 243

### 5 Approximation Methods in Atmospheric 3D Radiative Transfer, Part 1: Resolved Variability and Phenomenology

A.B. Davis and I.N. Polonsky ..... 283

---

## Part III Climate

---

### 6 Approximation Methods in Atmospheric 3D Radiative Transfer, Part 2: Unresolved Variability and Climate Applications

H.W. Barker and A.B. Davis ..... 343

### 7 3D Radiative Transfer in Stochastic Media

N. Byrne ..... 385

### 8 Effective Cloud Properties for Large-Scale Models

R.F. Cahalan ..... 425

**9 Broadband Irradiances and Heating Rates for Cloudy Atmospheres**  
H.W. Barker ..... 449

**10 Longwave Radiative Transfer in Inhomogeneous Cloud Layers**  
R.G. Ellingson and E.E. Takara ..... 487

---

**Part IV Remote Sensing**

---

**11 3D Radiative Transfer in Satellite Remote Sensing of Cloud Properties**  
R. Davies ..... 523

**12 Horizontal Fluxes and Radiative Smoothing**  
A. Marshak and A.B. Davis ..... 543

**13 Photon Paths and Cloud Heterogeneity: An Observational Strategy  
to Assess Effects of 3D Geometry on Radiative Transfer**  
G.L. Stephens, A.K. Heidinger and P.M. Gabriel ..... 587

**14 3D Radiative Transfer in Vegetation Canopies and Cloud-  
Vegetation Interaction**  
Y. Knyazikhin, A. Marshak and R.B. Myneni ..... 617

**Appendix: Scale-by-Scale Analysis and Fractal Cloud Models**  
A. Marshak and A.B. Davis ..... 653

**Epilogue: What Happens Next?**  
..... 665

**Notations** ..... 671

**Index** ..... 683

---

## List of Contributors

**Howard W. Barker**

Meteorological Service of Canada  
Downsview, Ontario M3H 5T4  
Canada  
Howard.Barker@ec.gc.ca

**Nelson Byrne**

Science Applications International  
Corporation  
San Diego, California 92121  
USA  
nbyrne@pacbell.net

**Robert F. Cahalan**

NASA-Goddard Space Flight Center  
Climate and Radiation Branch  
Code 613.2  
Greenbelt, Maryland 20771  
USA  
Robert.F.Cahalan@nasa.gov

**Eugene E. Clothiaux**

Department of Meteorology  
Penn State University  
University Park, Pennsylvania 16802  
USA  
cloth@essc.psu.edu

**Roger Davies**

Jet Propulsion Laboratory  
Pasadena, California 91109  
USA  
Roger.Davies@jpl.nasa.gov

**Anthony B. Davis**

Los Alamos National Laboratory  
Space and Remote Sensing Sciences  
Group (ISR-2)  
Los Alamos, New Mexico 87545  
USA  
adavis@lanl.gov

**Robert G. Ellingson**

Department of Meteorology  
Florida State University  
Tallahassee, Florida 32306  
USA  
bobe@met.fsu.edu

**K. Franklin Evans**

Program in Atmospheric and Oceanic  
Sciences  
University of Colorado  
Boulder, Colorado 8030  
USA  
evans@nit.colorado.edu

**Philip M. Gabriel**

Department of Atmospheric Science  
Colorado State University  
Fort Collins, Colorado 80523  
USA  
gabriel@atmos.colostate.edu

**Andrew K. Heidinger**

UW/CIMSS/NOAA  
1225 West Dayton St.  
Madison, Wisconsin 53706  
USA  
Andrew.Heidinger@noaa.gov

**Yuri Knyazikhin**

Department of Geography  
Boston University  
Boston, Massachusetts 02215  
USA  
jknjazi@bu.edu

**Alexei V. Korolev**

Meteorological Service of Canada  
Downsview, Ontario M3H 5T4  
Canada  
Alexei.Korolev@rogers.com

**Alexander Marshak**

NASA-Goddard Space Flight Center  
Climate and Radiation Branch  
Code 613.2  
Greenbelt, Maryland 20771  
USA  
Alexander.Marshak@nasa.gov

**Ranga B. Myneni**

Department of Geography  
Boston University  
Boston, Massachusetts 02215  
USA  
rmyneni@bu.edu

**Igor N. Polonsky**

Los Alamos National Laboratory  
Space and Remote Sensing Sciences  
Group (ISR-2)  
Los Alamos, New Mexico 87545  
USA  
polonsky@lanl.gov

**Graeme L. Stephens**

Department of Atmospheric Science  
Colorado State University  
Fort Collins, Colorado 80523  
USA  
stephens@atmos.colostate.edu

**Ezra E. Takara**

Department of Meteorology  
Florida State University  
Tallahassee, Florida 32306  
USA  
etakara@met.fsu.edu

**Warren J. Wiscombe**

NASA-Goddard Space Flight Center  
Climate and Radiation Branch  
Code 613.2  
Greenbelt, Maryland 20771  
USA  
Warren.J.Wiscombe@nasa.gov

Part I

## **Preliminaries**