

METEOROLOGICAL MONOGRAPHS

BOARD OF EDITORS

Assistant Editor

THOMAS A. GLEESON
Florida State University

Editor-in-Chief

WERNER A. BAUM
Florida State University

Assistant to the Editor

WHEATON M. COWARD, JR.
American Meteorological Society

Associate Editors

DAVID ATLAS
A. F. Cambridge Research Center

GERALD L. BARGER
U. S. Weather Bureau

LOUIS J. BATTAN
University of Arizona

FREDERIC A. BERRY
Aerometric Research Inc.

ROSCOE R. BRAHAM, JR.
University of Chicago

RICHARD A. CRAIG
Florida State University

GEORGE P. CRESSMAN
U. S. Weather Bureau

A. NELSON DINGLE
University of Michigan

GORDON E. DUNN
U. S. Weather Bureau

ROBERT G. FLEAGLE
University of Washington

F. N. FRENKIEL
J. Hopkins Applied Physics Lab.

W. LAWRENCE GATES
University of California at L.A.

JOSEPH J. GEORGE
Eastern Air Lines

MAURICE H. HALSTEAD
Navy Electronics Laboratory

BERNHARD HAURWITZ
University of Colorado

SEYMOUR L. HESS
Florida State University

HENRY G. HOUGHTON
Mass. Institute of Technology

WOODROW C. JACOBS
Library of Congress

HELMUT E. LANDSBERG
U. S. Weather Bureau

JAMES E. MILLER
New York University

JEROME NAMIAS
U. S. Weather Bureau

HANS NEUBERGER
Pennsylvania State University

CHESTER W. NEWTON
University of Chicago

HANS A. PANOFSKY
Pennsylvania State University

NORMAN G. PHILLIPS
Mass. Institute of Technology

RICHARD J. REED
University of Washington

HERBERT RIEHL
University of Chicago

HENRY STOMMEL
Woods Hole Ocean. Instn.

VERNER E. SUOMI
University of Wisconsin

HARRY WEXLER
U. S. Weather Bureau

METEOROLOGICAL MONOGRAPHS, a serial publication of the American Meteorological Society, serves as a medium for original papers, survey articles, and other material in meteorology and closely related fields; it is intended for material which is better suited in length or nature for publication in monograph form than for publication in the *Journal of Meteorology*, in the *Bulletin of the American Meteorological Society* or in *Weatherwise*. A METEOROLOGICAL MONOGRAPH may consist of a single paper or of a group of papers concerned with a single general topic.

INFORMATION FOR CONTRIBUTORS

Manuscripts for the METEOROLOGICAL MONOGRAPHS should be sent directly to the Editor: Werner A. Baum, Florida State University, Tallahassee, Florida. Manuscripts may be submitted by persons of any nationality who are members or nonmembers of the Society, but only manuscripts in the English language can be accepted. Every manuscript submitted is reviewed and in no case does the editor advise the author as to acceptability until at least one review has been obtained. Authors will receive galley proof but not page proof.

Manuscripts. The manuscript must be complete and in final form when submitted. It must be original typewritten copy on one side only of white paper sheets $8\frac{1}{2} \times 11$ inches, consecutively numbered; double spacing and wide margins are essential. Carbon copy and single spacing are not acceptable.

Each manuscript may include the following components, which should be presented in the order listed. Of these, the table of contents; title, author's name and affiliation; abstract; text; references; and legends are obligatory.

1. Title page. This will be prepared by the editor if the manuscript is accepted for publication.

2. Preface or foreword. A preface may be contributed by the sponsors of the investigation, or by some other interested group or individual. The preface should indicate the origin of the study and should present other facts of general interest which emphasize its importance and significance.

3. Table of contents. Chapter, section, and subsection headings should all be listed in the table of contents.

4. Title, author's name and affiliation. The affiliation should be stated as concisely as possible and should not constitute a complete address. The date of receipt of the manuscript is supplied by the editor.

5. Abstract. This should summarize the principal hypotheses, methods, and conclusions of the investigation. It should not include mathematical symbols or references to equation numbers, since the abstract is sometimes quoted verbatim in abstracting or reviewing journals.

6. Text. For one of a group of papers which together constitute a MONOGRAPH, it is sufficient to divide the text into sections, each with a separate heading, numbered consecutively. The section heading should be placed on a separate line, flush with the margin, and should *not* be underlined. Subsection headings, if needed, should be located at the beginning of certain paragraphs and underlined.

7. References. References should be arranged alphabetically and designated by numbers. The numbers are enclosed by brackets in the text but not in the alphabetical listing. When two or more references are involved, separate the numbers by semicolons: thus, "previous investigations [3; 12; 27] have shown . . ."

Each reference listed should be complete and in the following form. For an article: author(s), year, title of article, title of serial publication (underlined), volume

METEOROLOGICAL MONOGRAPHS

Volume 4

August 1960

Number 23

ATMOSPHERIC RADIATION TABLES

by

Walter M. Elsasser

with

Margaret F. Culbertson

*Sponsored by the Geophysics Research Directorate
of the AF Cambridge Research Laboratories,
Air Force Research Division (ARDC)
under Contract AF 19(604)-2413*

**PUBLISHED BY THE AMERICAN METEOROLOGICAL SOCIETY
45 BEACON ST., BOSTON 8, MASS.**

ISBN 978-1-940033-48-8 (eBook)

DOI 10.1007/978-1-940033-48-8

METEOROLOGICAL MONOGRAPHS

BOARD OF EDITORS

Assistant Editor

THOMAS A. GLEESON
Florida State University

Editor-in-Chief

WERNER A. BAUM
Florida State University

Assistant to the Editor

WHEATON M. COWARD, JR.
American Meteorological Society

Associate Editors

DAVID ATLAS
A. F. Cambridge Research Center

GERALD L. BARGER
U. S. Weather Bureau

LOUIS J. BATTAN
University of Arizona

FREDERIC A. BERRY
Aerometric Research Inc.

ROSCOE R. BRAHAM, JR.
University of Chicago

RICHARD A. CRAIG
Florida State University

GEORGE P. CRESSMAN
U. S. Weather Bureau

A. NELSON DINGLE
University of Michigan

GORDON E. DUNN
U. S. Weather Bureau

ROBERT G. FLEAGLE
University of Washington

F. N. FRENKIEL
J. Hopkins Applied Physics Lab.

W. LAWRENCE GATES
University of California at L.A.

JOSEPH J. GEORGE
Eastern Air Lines

MAURICE H. HALSTEAD
Navy Electronics Laboratory

BERNHARD HAURWITZ
University of Colorado

SEYMOUR L. HESS
Florida State University

HENRY G. HOUGHTON
Mass. Institute of Technology

WOODROW C. JACOBS
Library of Congress

HELMUT E. LANDSBERG
U. S. Weather Bureau

JAMES E. MILLER
New York University

JEROME NAMIAS
U. S. Weather Bureau

HANS NEUBERGER
Pennsylvania State University

CHESTER W. NEWTON
University of Chicago

HANS A. PANOFSKY
Pennsylvania State University

NORMAN G. PHILLIPS
Mass. Institute of Technology

RICHARD J. REED
University of Washington

HERBERT RIEHL
University of Chicago

HENRY STOMMEL
Woods Hole Ocean. Instn.

VERNER E. SUOMI
University of Wisconsin

HARRY WEXLER
U. S. Weather Bureau

METEOROLOGICAL MONOGRAPHS, a serial publication of the American Meteorological Society, serves as a medium for original papers, survey articles, and other material in meteorology and closely related fields; it is intended for material which is better suited in length or nature for publication in monograph form than for publication in the *Journal of Meteorology*, in the *Bulletin of the American Meteorological Society* or in *Weatherwise*. A METEOROLOGICAL MONOGRAPH may consist of a single paper or of a group of papers concerned with a single general topic.

PREFACE

In 1942, the author published a monograph entitled "Heat Transfer by Infrared Radiation in the Atmosphere," which was rather favorably received by the meteorological public. The war terminated this particular work, and during it and thereafter the author became engaged in other scientific pursuits not directly related to atmospheric radiation. In the meantime, a vast literature has grown up around the subject, dealing with laboratory experiments as well as theoretical analysis, not to speak of the applications to the atmosphere itself. From the fall of 1950 until 1954, the author, while at the University of Utah, was engaged in a project sponsored by the Air Force Cambridge Research Center whose aim it was in part to extend the methods used earlier for water vapor so that they were applicable to carbon dioxide and ozone. Very extensive new laboratory data on all three optically active atmospheric gases have become known in the last seven or eight years. This finally suggested a new edition of the earlier monograph, and the task was begun in the summer of 1957 at the Scripps Institution of Oceanography, again under the sponsorship of the Air Force Cambridge Research Center.

The present monograph is a second edition of the earlier one in the limited sense that the methods used to determine radiative fluxes in the atmosphere have been retained with only very minor changes. Approximations much more refined but also much more cumbersome to handle than the linear techniques of the 1942 work have been omitted. Instead, radiation tables have been calculated on the basis of the available data, practically all of them fairly new, for the 15- μ CO₂ band, the combined 9.6- μ and 9.0- μ ozone bands, the 6.3- μ water-vapor band, the rotational water-vapor band, and finally for the overall water-vapor spectrum. The only difference, in principle, from the earlier treatment lies in the use of a linear pressure reduction throughout, in place of the former square-root reduction. In the text, the review of the basic theory of band structure and band absorption has been somewhat enlarged. On the other hand, Part III of the earlier monograph which dealt mainly with radiation measurements in the atmosphere itself has been omitted, partly because the new tables are based on laboratory data, but largely because the

literature on the subject has swollen to such dimensions that it would be impossible to do justice to it within the confines of this monograph.

Owing to many other obligations, the author has been unable to keep up in detail with the proliferating literature on atmospheric radiation. A purely formal bibliography based on a search of the abstracting literature seemed out of place in a work of this limited character. We have therefore restricted the bibliography to papers that are actually quoted in the text. It is possible, though not too probable, that an occasional paper which has a direct bearing on our work might have been overlooked, and the author apologizes in advance for such omissions.

Another restriction of the present monograph concerns the fact that we give only tables and no nomograms (charts). This is based on the view that a work like the present by its very nature addresses itself not so much to the practical forecaster as to the scientific investigator of the atmosphere. The latter will almost invariably spend some time and effort on the subject of radiative transfer if he becomes engaged in it at all. Given the very numerous graphical or numerical schemes that may be used for this purpose, depending on individual tastes, we felt it to be preferable to leave the construction of nomographs to the investigators concerned. With modern methods of reproduction, this is a relatively simple and cheap task that can be performed quite rapidly.

The very extensive computational work, including the involved two-dimensional smoothing of the radiation tables, was done by Miss Margaret Culbertson, M.A. Without her consistent accurate performance, this monograph could not have been written.

We are greatly indebted to the Thermal Radiation Laboratory of the Air Force Cambridge Research Center for their financial support, and in particular to Drs. John N. Howard, J. I. King, and P. R. Gast for their personal encouragement. This assistance and encouragement has been invaluable in completing the work.

WALTER M. ELSASSER

SCRIPPS INSTITUTION OF OCEANOGRAPHY
LA JOLLA, CALIFORNIA
FEBRUARY 1960

CONTENTS

| | PAGE |
|---|------|
| I. INTRODUCTION | 1 |
| II. PRINCIPLES OF RADIATIVE TRANSFER | 3 |
| 1. Kirchoff's Law, Planck's Law, the equation of transfer | 3 |
| 2. A single spectral line | 4 |
| 3. Periodic band pattern | 5 |
| 4. Statistical band model | 6 |
| 5. Pressure. Semi-empirical method | 7 |
| 6. Stratified medium | 8 |
| 7. Uniform isothermal layer | 9 |
| III. PHYSICS OF THE ATMOSPHERIC BANDS | 10 |
| 1. Spectroscopic characteristics | 10 |
| 2. The shape of spectral lines | 12 |
| 3. Local equilibrium and blackness | 14 |
| 4. Temperature dependence of band contour | 15 |
| IV. LABORATORY TRANSMISSIVITIES | 16 |
| 1. Formulary | 16 |
| 2. Carbon dioxide | 16 |
| 3. Ozone | 21 |
| 4. Water vapor | 24 |
| V. THE TRANSFER EQUATIONS, TABLES AND CHARTS | 30 |
| 1. Integration of the transfer equations | 30 |
| 2. Construction of tables and charts | 31 |
| 3. Use of a radiation chart | 32 |
| 4. Radiative cooling | 34 |
| 5. The carbon-dioxide—water overlap | 34 |
| VI. NUMERICAL TABLES | 36 |
| Table 1. dB_{ν}/dT | 37 |
| Tables 2–7. Beam and slab transmissivities | 38 |
| Tables 8–10. Generalized absorption coefficients | 39 |
| Tables 11–12. Radiation and flux-divergence tables for CO_2 | 39 |
| Tables 13–14. Radiation and flux-divergence tables for O_3 | 40 |
| Tables 15–17. Radiation tables for separate bands of H_2O | 41 |
| Tables 18–19. Radiation and flux-divergence tables for H_2O | 42 |
| Table 20. Chart areas for -80C | 42 |
| Tables 21–22. Water-vapor—carbon-dioxide overlap | 43 |