Contents

Preface IX

- 1 The Earth's Energy Budget and Climate Change 1
- 1.1 Introduction 1
- 1.2 Radiative Heating of the Atmosphere 2
- 1.3 Global Energy Budget 3
- 1.4 The Window-Gray Approximation and the Greenhouse Effect 6

v

- 1.5 Climate Sensitivity and Climate Feedbacks 8
- 1.6 Radiative Time Constant 12
- 1.7 Composition of the Earth's Atmosphere 14
- 1.8 Radiation and the Earth's Mean Temperature Profile 19
- 1.9 The Spatial Distribution of Radiative Heating and Circulation 32
- 1.10 Summary and Outlook 35 References 39

2 Radiation and Its Sources 41

- 2.1 Light as an Electromagnetic Wave 41
- 2.2 Radiation from an Oscillating Dipole, Radiance, and Radiative Flux 42
- 2.3 Radiometry 47
- 2.4 Blackbody Radiation: Light as a Photon 50
- 2.5 Incident Sunlight 57
 - References 63

3 Transfer of Radiation in the Earth's Atmosphere 65

- 3.1 Cross Sections 65
- 3.2 Scattering Cross Section and Scattering Phase Function 68
- 3.3 Elementary Principles of Light Scattering 71
- 3.4 Equation of Radiative Transfer 77
- 3.5 Radiative Transfer Equations for Solar and Terrestrial Radiation 80 References 82

VI Contents

4	Solutions to the Equation of Radiative Transfer 85
4.1	Introduction 85
4.2	Formal Solution to the Equation of Radiative Transfer 86
4.3	Solution for Thermal Emission 88
4.4	Infrared Fluxes and Heating Rates 93
4.5	Formal Solution for Scattering and Absorption 102
4.6	Single Scattering Approximation 103
4.7	Fourier Decomposition of the Radiative Transfer Equation 110
4.8	The Legendre Series Representation and the Eddington
110	Approximation 112
4.9	Adding Layers in the Eddington Approximation 121
4.10	Adding a Surface with a Nonzero Albedo in the Eddington
1110	Approximation 123
4.11	Clouds in the Thermal Infrared 124
4.12	<i>Optional</i> Separation of Direct and Diffuse Radiances 126
4.13	<i>Optional</i> Separating the Diffusely Scattered Light from the Direct
1.10	Beam in the Eddington and Two-Stream Approximations 127
4.14	Optional The δ -Eddington Approximation 130
4.15	<i>Optional</i> The Discrete Ordinate Method and DISORT 135
4.16	Optional Adding-Doubling Method 138
4.17	<i>Optional</i> Monte Carlo Simulations 140
	References 146
5	Treatment of Molecular Absorption in the Atmosphere 149
5 5.1	Treatment of Molecular Absorption in the Atmosphere 149 Spectrally Averaged Transmissions 149
5.1	Spectrally Averaged Transmissions 149
5.1 5.2	Spectrally Averaged Transmissions <i>149</i> Molecular Absorption Spectra <i>151</i>
5.1 5.2	Spectrally Averaged Transmissions <i>149</i> Molecular Absorption Spectra <i>151</i> Positions and Strengths of Absorption Lines within
5.1 5.2 5.3	Spectrally Averaged Transmissions 149 Molecular Absorption Spectra 151 Positions and Strengths of Absorption Lines within Vibration-Rotation Bands 155
5.1 5.2 5.3 5.4	Spectrally Averaged Transmissions 149 Molecular Absorption Spectra 151 Positions and Strengths of Absorption Lines within Vibration-Rotation Bands 155 Shapes of Absorption Lines 159
5.1 5.2 5.3 5.4 5.5	Spectrally Averaged Transmissions 149 Molecular Absorption Spectra 151 Positions and Strengths of Absorption Lines within Vibration-Rotation Bands 155 Shapes of Absorption Lines 159 Doppler Broadening and the Voigt Line Shape 162
5.1 5.2 5.3 5.4 5.5 5.6	Spectrally Averaged Transmissions149Molecular Absorption Spectra151Positions and Strengths of Absorption Lines withinVibration-Rotation Bands155Shapes of Absorption Lines159Doppler Broadening and the Voigt Line Shape162Average Absorptivity for a Single, Weak Absorption Line163
5.1 5.2 5.3 5.4 5.5 5.6	Spectrally Averaged Transmissions 149 Molecular Absorption Spectra 151 Positions and Strengths of Absorption Lines within Vibration-Rotation Bands 155 Shapes of Absorption Lines 159 Doppler Broadening and the Voigt Line Shape 162 Average Absorptivity for a Single, Weak Absorption Line 163 Average Absorptivity for a Single, Strong, Pressure-Broadened
5.1 5.2 5.3 5.4 5.5 5.6 5.7	Spectrally Averaged Transmissions 149 Molecular Absorption Spectra 151 Positions and Strengths of Absorption Lines within Vibration-Rotation Bands 155 Shapes of Absorption Lines 159 Doppler Broadening and the Voigt Line Shape 162 Average Absorptivity for a Single, Weak Absorption Line 163 Average Absorptivity for a Single, Strong, Pressure-Broadened Absorption Line 164
5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8	Spectrally Averaged Transmissions 149 Molecular Absorption Spectra 151 Positions and Strengths of Absorption Lines within Vibration-Rotation Bands 155 Shapes of Absorption Lines 159 Doppler Broadening and the Voigt Line Shape 162 Average Absorptivity for a Single, Weak Absorption Line 163 Average Absorptivity for a Single, Strong, Pressure-Broadened Absorption Line 164 Treatment of Inhomogeneous Atmospheric Paths 166
5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8	Spectrally Averaged Transmissions 149 Molecular Absorption Spectra 151 Positions and Strengths of Absorption Lines within Vibration-Rotation Bands 155 Shapes of Absorption Lines 159 Doppler Broadening and the Voigt Line Shape 162 Average Absorptivity for a Single, Weak Absorption Line 163 Average Absorptivity for a Single, Strong, Pressure-Broadened Absorption Line 164 Treatment of Inhomogeneous Atmospheric Paths 166 Average Transmissivities for Bands of Nonoverlapping Absorption
5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9	Spectrally Averaged Transmissions 149 Molecular Absorption Spectra 151 Positions and Strengths of Absorption Lines within Vibration-Rotation Bands 155 Shapes of Absorption Lines 159 Doppler Broadening and the Voigt Line Shape 162 Average Absorptivity for a Single, Weak Absorption Line 163 Average Absorptivity for a Single, Strong, Pressure-Broadened Absorption Line 164 Treatment of Inhomogeneous Atmospheric Paths 166 Average Transmissivities for Bands of Nonoverlapping Absorption Lines 169
5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9	Spectrally Averaged Transmissions 149 Molecular Absorption Spectra 151 Positions and Strengths of Absorption Lines within Vibration-Rotation Bands 155 Shapes of Absorption Lines 159 Doppler Broadening and the Voigt Line Shape 162 Average Absorptivity for a Single, Weak Absorption Line 163 Average Absorptivity for a Single, Strong, Pressure-Broadened Absorption Line 164 Treatment of Inhomogeneous Atmospheric Paths 166 Average Transmissivities for Bands of Nonoverlapping Absorption Lines 169 Approximate Treatments of Average Transmissivities for
5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10	Spectrally Averaged Transmissions149Molecular Absorption Spectra151Positions and Strengths of Absorption Lines withinVibration-Rotation Bands155Shapes of Absorption Lines159Doppler Broadening and the Voigt Line Shape162Average Absorptivity for a Single, Weak Absorption Line163Average Absorptivity for a Single, Strong, Pressure-BroadenedAbsorption Line164Treatment of Inhomogeneous Atmospheric Paths166Average Transmissivities for Bands of Nonoverlapping AbsorptionLines169Approximate Treatments of Average Transmissivities forOverlapping Lines171
5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11	Spectrally Averaged Transmissions149Molecular Absorption Spectra151Positions and Strengths of Absorption Lines withinVibration-Rotation Bands155Shapes of Absorption Lines159Doppler Broadening and the Voigt Line Shape162Average Absorptivity for a Single, Weak Absorption Line163Average Absorptivity for a Single, Strong, Pressure-BroadenedAbsorption Line164Treatment of Inhomogeneous Atmospheric Paths166Average Transmissivities for Bands of Nonoverlapping AbsorptionLines169Approximate Treatments of Average Transmissivities forOverlapping Lines171Exponential Sum-Fit and Correlated k-Distribution Methods177
5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11	Spectrally Averaged Transmissions 149 Molecular Absorption Spectra 151 Positions and Strengths of Absorption Lines within Vibration-Rotation Bands 155 Shapes of Absorption Lines 159 Doppler Broadening and the Voigt Line Shape 162 Average Absorptivity for a Single, Weak Absorption Line 163 Average Absorptivity for a Single, Strong, Pressure-Broadened Absorption Line 164 Treatment of Inhomogeneous Atmospheric Paths 166 Average Transmissivities for Bands of Nonoverlapping Absorption Lines 169 Approximate Treatments of Average Transmissivities for Overlapping Lines 171 Exponential Sum-Fit and Correlated <i>k</i> -Distribution Methods 177 Treatment of Overlapping Molecular Absorption Bands 182 References 184
5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11	Spectrally Averaged Transmissions 149 Molecular Absorption Spectra 151 Positions and Strengths of Absorption Lines within Vibration-Rotation Bands 155 Shapes of Absorption Lines 159 Doppler Broadening and the Voigt Line Shape 162 Average Absorptivity for a Single, Weak Absorption Line 163 Average Absorptivity for a Single, Strong, Pressure-Broadened Absorption Line 164 Treatment of Inhomogeneous Atmospheric Paths 166 Average Transmissivities for Bands of Nonoverlapping Absorption Lines 169 Approximate Treatments of Average Transmissivities for Overlapping Lines 171 Exponential Sum-Fit and Correlated <i>k</i> -Distribution Methods 177 Treatment of Overlapping Molecular Absorption Bands 182 References 184 Absorption of Solar Radiation by the Earth's Atmosphere and
5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11 5.12 6	Spectrally Averaged Transmissions149Molecular Absorption Spectra151Positions and Strengths of Absorption Lines withinVibration-Rotation Bands155Shapes of Absorption Lines159Doppler Broadening and the Voigt Line Shape162Average Absorptivity for a Single, Weak Absorption Line163Average Absorptivity for a Single, Strong, Pressure-BroadenedAbsorption Line164Treatment of Inhomogeneous Atmospheric Paths166Average Transmissivities for Bands of Nonoverlapping AbsorptionLines169Approximate Treatments of Average Transmissivities forOverlapping Lines171Exponential Sum-Fit and Correlated k-Distribution Methods177Treatment of Overlapping Molecular Absorption Bands182References184Absorption of Solar Radiation by the Earth's Atmosphere andSurface185
5.1 5.2 5.3 5.4 5.5 5.6 5.7 5.8 5.9 5.10 5.11 5.12	Spectrally Averaged Transmissions 149 Molecular Absorption Spectra 151 Positions and Strengths of Absorption Lines within Vibration-Rotation Bands 155 Shapes of Absorption Lines 159 Doppler Broadening and the Voigt Line Shape 162 Average Absorptivity for a Single, Weak Absorption Line 163 Average Absorptivity for a Single, Strong, Pressure-Broadened Absorption Line 164 Treatment of Inhomogeneous Atmospheric Paths 166 Average Transmissivities for Bands of Nonoverlapping Absorption Lines 169 Approximate Treatments of Average Transmissivities for Overlapping Lines 171 Exponential Sum-Fit and Correlated <i>k</i> -Distribution Methods 177 Treatment of Overlapping Molecular Absorption Bands 182 References 184 Absorption of Solar Radiation by the Earth's Atmosphere and

- 6.2 Absorption of UV and Visible Sunlight by Ozone 186
- 6.3 Absorption of Sunlight by Water Vapor 191 References 201

7 Simplified Estimates of Emission 203

- 7.1 Introduction 203
- 7.2 Emission in the 15 μ m Band of CO₂ 203
- 7.3 Change in Emitted Flux due to Doubling of CO_2 209
- 7.4 Changes in Stratospheric Emission and Temperature Caused by a
- - References 217

Appendix A Useful Physical and Geophysical Constants 219

Appendix B Solving Differential Equations 221

- B.1 Simple Integration 221
- B.2 Integration Factor 221
- B.3 Second Order Differential Equations 223

Appendix C Integrals of the Planck Function 225

Appendix D Random Model Summations of Absorption LineParameters for the Infrared Bands of Carbon Dioxide227Reference229

Appendix E Ultraviolet and Visible Absorption Cross Sections of Ozone 231 References 231

Index 233