



# Radiation and Climate

I.M. VARDAVAS

*Department of Physics, University of Crete*

F.W. TAYLOR

*Atmospheric, Oceanic, and Planetary Physics, Clarendon Laboratory,  
University of Oxford*

**OXFORD**  
UNIVERSITY PRESS

## CONTENTS

<b>1</b>	<b>The climate system</b>	<b>1</b>
1.1	Introduction	1
1.2	Solar radiation	2
1.3	The atmosphere	3
1.4	Clouds and aerosols	6
1.5	Radiative equilibrium and radiative forcing	8
1.6	Atmospheric circulation	10
1.7	The hydrosphere and the cryosphere	12
1.7.1	Oceanic circulation	13
1.7.2	El Niño southern oscillation (ENSO)	15
1.7.3	North Atlantic oscillation (NAO)	17
1.7.4	Ice sheets	19
1.8	The land surface and biosphere	20
1.8.1	Land-surface albedo	20
1.8.2	Carbon dioxide sequestering	20
1.9	The climate record	21
1.9.1	Temperature trends	21
1.9.2	Sea-ice extent	21
1.9.3	Extreme events	22
1.9.4	Sea-level trends	24
1.10	Projections of future climate	24
1.10.1	Emission scenarios and global warming	26
1.10.2	Climate projections for the twenty-first century	27
1.11	Bibliography	30
1.11.1	Notes	30
1.11.2	References and further reading	31
<b>2</b>	<b>Atmospheric physics and thermodynamics</b>	<b>33</b>
2.1	Introduction	33
2.2	Atmospheric composition	34
2.2.1	Well-mixed species	34
2.2.2	Water vapour and ozone	35
2.2.3	Trace constituents	37
2.3	Pressure and hydrostatic equilibrium	39
2.4	Vapours and ideal gases	40
2.5	Vertical temperature structure	42
2.6	Thermodynamics of moist air	45
2.7	Condensation processes, clouds and aerosols	48
2.7.1	Criteria for vertical stability	48
2.7.2	Growth of cloud particles	49

2.7.3	Cloud particle size distributions	51
2.7.4	Aerosols	52
2.8	Bibliography	54
2.8.1	Notes	54
2.8.2	References and further reading	54
<b>3</b>	<b>Radiation-transfer theory</b>	<b>56</b>
3.1	Introduction	56
3.2	Basic definitions	56
3.2.1	The inverse square law	56
3.2.2	Radiance	58
3.2.3	Mean radiance and flux	59
3.2.4	Luminosity	60
3.3	Blackbody radiation	60
3.3.1	Planck's law	61
3.3.2	Stefan–Boltzmann law	61
3.3.3	Radiation energy density	62
3.3.4	Wien's displacement law	62
3.4	Absorption, emission and scattering	63
3.4.1	Absorption and emission	63
3.4.2	Scattering	64
3.4.3	The extinction coefficient and optical depth	65
3.4.4	Volume emission and Kirchoff's law	67
3.4.5	The source function and redistribution	68
3.4.6	Limiting forms of the redistribution function	68
3.4.7	Forms of the source function	71
3.5	The equation of radiation transfer	72
3.5.1	General form	72
3.5.2	Plane-parallel atmosphere	73
3.5.3	Solution for pure absorption	74
3.5.4	Solution for thermal emission	75
3.5.5	The diffusivity approximation	75
3.5.6	The Eddington and diffusion approximations	76
3.5.7	The Schuster–Schwarzschild approximation	78
3.5.8	General solutions for upwelling radiation	80
3.5.9	Schwarzschild–Milne equations	81
3.5.10	Grey atmospheres in radiative equilibrium	82
3.6	Bibliography	84
3.6.1	Notes	84
3.6.2	References and further reading	85
<b>4</b>	<b>Thermal infra-red transfer in the atmosphere</b>	<b>86</b>
4.1	Introduction	86
4.2	Spectral lines	86
4.2.1	Line broadening mechanisms	87

4.2.2	The Einstein coefficients	91
4.2.3	Line absorptance or equivalent width	93
4.2.4	The curve of growth	95
4.3	Rotational lines and bands	97
4.3.1	Effect of degeneracy	100
4.4	Vibrational lines and bands	101
4.4.1	The harmonic vibrator	101
4.4.2	The anharmonic vibrator	101
4.4.3	The anharmonic vibrator–rotator	104
4.4.4	Absorption bands of polyatomic molecules	106
4.5	Band absorptance formulations	107
4.5.1	Doppler–broadened rotational lines	107
4.5.2	Collisionally–broadened rotational lines	109
4.5.3	Temperature dependence of absorptance	111
4.6	Important greenhouse gases	114
4.6.1	Bands in the terrestrial infra-red region	114
4.6.2	Water vapour	114
4.6.3	Carbon dioxide	115
4.6.4	Ozone	116
4.6.5	Methane, ammonia and N <sub>2</sub> O	116
4.7	The HITRAN database	117
4.7.1	Application to N <sub>2</sub> O	119
4.8	Clear-sky fluxes	119
4.8.1	Upwelling fluxes	121
4.8.2	Downwelling fluxes	121
4.8.3	Outgoing flux at TOA	122
4.9	Cloudy-sky fluxes	122
4.9.1	Outgoing flux above a cloud layer	123
4.9.2	Downwelling flux at the Earth's surface	123
4.10	Computation of fluxes	124
4.10.1	Data requirements	124
4.10.2	Curtis–Godson approximation	125
4.11	Bibliography	126
4.11.1	Notes	126
4.11.2	References and further reading	126
5	Incoming solar radiation	128
5.1	Introduction	128
5.2	The Sun as a main-sequence star	129
5.2.1	Stellar properties	129
5.2.2	Total solar irradiance	131
5.2.3	The solar cycle	132
5.2.4	Solar spectral irradiance	134
5.3	Solar evolution	137

5.3.1	Protostar to main sequence	137
5.3.2	Beyond the main sequence	138
5.4	Solar luminosity evolution	139
5.4.1	The role of mean molecular weight	139
5.4.2	The faint–young–Sun paradox	140
5.5	Solar ultraviolet flux evolution	140
5.5.1	Stellar activity and rotation	140
5.5.2	Rotation with spectral type and age	142
5.5.3	Rossby number with spectral type and age	142
5.5.4	XUV–Ly $\alpha$ emission and Rossby number	143
5.5.5	Solar XUV and Ly– $\alpha$ emission flux evolution	147
5.5.6	Solar photospheric irradiance evolution	149
5.6	Solar flux at the Earth’s orbit	151
5.6.1	The Earth’s elliptical orbit	151
5.6.2	The plane of the ecliptic	151
5.6.3	Sun–Earth distance and solar longitude	152
5.6.4	The equation of time	153
5.6.5	Incoming radiation at TOA	155
5.6.6	Global distribution of incoming radiation	156
5.7	Bibliography	158
5.7.1	Notes	158
5.7.2	References and further reading	159
<b>6</b>	<b>Solar radiation transfer in the atmosphere</b>	<b>163</b>
6.1	Introduction	163
6.2	Atmospheric molecular absorption	164
6.2.1	Ultraviolet–visible absorption	164
6.2.2	Near-infra-red absorption	166
6.3	Particle absorption and scattering	168
6.3.1	Mie scattering	169
6.3.2	The Mie scattering functions	174
6.3.3	Rayleigh scattering	177
6.4	Clouds absorption and scattering	179
6.4.1	Cloud types	179
6.4.2	Visible scattering	180
6.4.3	Near-infra-red absorption and scattering	181
6.5	Aerosol absorption and scattering	181
6.5.1	Aerosol radiative properties	181
6.5.2	Particle size and Ångstrom parameter	182
6.5.3	Aerosol fine and coarse modes	184
6.6	Surface reflection	187
6.6.1	Snell and Fresnel laws	187
6.7	Multiple scattering solution for inhomogeneous layers	189
6.7.1	Isotropic scattering solution	190

6.7.2	Thomas algorithm	190
6.7.3	Anisotropic scattering solution	191
6.7.4	Atmospheres with clouds and aerosols	196
6.7.5	Sample computations	197
6.8	Bibliography	198
6.8.1	Notes	198
6.8.2	References and further reading	198
7	<b>Atmospheric photochemistry</b>	201
7.1	Introduction	201
7.2	The continuity equation	202
7.3	Brownian and turbulent diffusion	203
7.3.1	Fick's law	203
7.3.2	Bimolecular diffusion	204
7.3.3	Diffusive flux	205
7.4	Surface deposition	208
7.4.1	Surface deposition loss rate	208
7.4.2	Dry deposition velocities	209
7.5	Surface emission	211
7.6	Photolysis	212
7.6.1	Photolysis rate	212
7.6.2	Quantum yield	213
7.6.3	O <sub>2</sub> photolysis	214
7.6.4	O <sub>3</sub> photolysis	217
7.6.5	H <sub>2</sub> O photolysis	218
7.6.6	CO <sub>2</sub> photolysis	219
7.6.7	CH <sub>4</sub> photolysis	220
7.6.8	Atmospheric photolysis rates	221
7.7	Collisionally induced reactions	222
7.7.1	Types of reactions	222
7.7.2	Bimolecular reactions	223
7.7.3	Termolecular reactions	225
7.8	Ozone photochemistry	226
7.8.1	The Chapman mechanism	226
7.8.2	N <sub>2</sub> O and NO <sub>x</sub> photochemistry	227
7.8.3	Water vapour and HO <sub>x</sub> photochemistry	229
7.8.4	Chlorine and ClO <sub>x</sub> photochemistry	232
7.8.5	Polar stratospheric clouds	234
7.9	Methane and hydrogen photochemistry	235
7.9.1	H <sub>2</sub> in the atmosphere	235
7.9.2	Effects of increasing CH <sub>4</sub> emission	236
7.9.3	Effects of increasing CO <sub>2</sub> levels	237
7.10	Bibliography	238
7.10.1	Notes	238

7.10.2 References and further reading	239
<b>8 The Earth's radiation budget</b>	245
8.1 Introduction	245
8.2 Model input data	248
8.2.1 Cloud radiative properties	248
8.2.2 Cloud data sets	249
8.2.3 Water vapour and temperature profiles	251
8.2.4 Other greenhouse gases	252
8.2.5 Surface properties	253
8.2.6 Aerosol particles	254
8.3 Validation data	255
8.3.1 Global energy balance archive	256
8.3.2 Baseline radiation network	257
8.3.3 ERBE data	257
8.4 Outgoing solar radiation at TOA	259
8.4.1 Planetary albedo	259
8.4.2 Global distribution	261
8.4.3 Zonal–seasonal variation	262
8.4.4 Mean annual latitudinal variation	263
8.4.5 Seasonal variation	264
8.4.6 Mean annual hemispherical variation	266
8.4.7 Time series of planetary albedo	266
8.5 The shortwave radiation budget at surface	267
8.5.1 Global distribution	267
8.5.2 Zonal–seasonal variation	269
8.5.3 Latitudinal and seasonal variation	270
8.5.4 Validation with observations	270
8.5.5 Mean annual hemispherical variation	271
8.5.6 Long-term anomaly	272
8.5.7 Sensitivity analysis	274
8.6 Shortwave aerosol radiative forcing	275
8.6.1 Aerosol forcing at TOA	276
8.6.2 Aerosol forcing of atmospheric absorption	277
8.6.3 Aerosol forcing at the Earth's surface	278
8.6.4 Mean annual hemispherical aerosol forcings	279
8.7 Longwave radiation budget at TOA	280
8.7.1 Global distribution	281
8.7.2 Zonal–seasonal variation	281
8.7.3 Latitudinal and seasonal variation	282
8.7.4 Log–term hemispherical and global means	282
8.8 Longwave radiation budget at surface	283
8.8.1 Global distribution	284
8.8.2 Zonal, latitudinal and seasonal variations	285

8.8.3	Long-term anomaly	286
8.8.4	Long-term hemispherical and global means	287
8.8.5	Sensitivity analysis	288
8.9	Mediterranean Sea heat budget	290
8.9.1	The heat budget equation	291
8.9.2	Latent and sensible heat flux	292
8.9.3	Sea data for computing heat storage	293
8.9.4	Data for computing turbulent fluxes	294
8.9.5	Radiation fluxes	296
8.9.6	Heat storage	297
8.9.7	Turbulent fluxes	297
8.9.8	Seasonal evaporation rate	299
8.9.9	Annual evaporation rate	299
8.9.10	Comparison with Red and Black Seas	300
8.10	Bibliography	301
8.10.1	Notes	301
8.10.2	References and further reading	302
9	<b>Theory of radiation measurements</b>	310
9.1	Introduction	310
9.2	Detectors	311
9.3	Thermal detectors	314
9.4	Photon detectors	320
9.4.1	Photoconductive detectors	321
9.4.2	Photovoltaic detectors	323
9.5	Detector arrays and charge coupled devices	325
9.6	Properties of IR systems	325
9.6.1	Spectral properties	326
9.6.2	Wavelength calibration	328
9.6.3	Geometrical optical properties	328
9.6.4	Radiometric properties	331
9.7	Radiometric performance	333
9.7.1	Signal-to-noise ratio	333
9.7.2	A generalized radiometer	336
9.7.3	A realistic radiometer	337
9.7.4	Spectrometers and interferometers	340
9.8	Bibliography	343
9.8.1	Notes	343
9.8.2	References and further reading	343
10	<b>Climate observations by radiometry–spectrometry</b>	345
10.1	Introduction	345
10.2	Surface radiation budget: the pyranometer	346
10.3	Solar irradiance: ACRIM	350
10.4	TOA radiation budget: ERB, CERES and GERB	351

10.5 Sea surface temperature: ATSR	355
10.6 Surface properties: Thematic Mapper and MODIS	358
10.7 Atmospheric temperature: HIRS and AIRS	361
10.8 Atmospheric composition: IRIS, ATMOS and TES	366
10.9 Detection of climate change	370
10.10 Bibliography	374
10.10.1 Notes	374
10.10.2 References and further reading	374
<b>11 Climate modelling</b>	<b>377</b>
11.1 Introduction	377
11.2 Simple climate models	378
11.2.1 Global energy balance models	378
11.2.2 Simple greenhouse models	380
11.3 Radiative–convective climate models	385
11.3.1 Convective versus radiative equilibrium	385
11.3.2 Convective equilibrium	386
11.3.3 Radiative equilibrium	388
11.3.4 Climatic effects of increasing CO <sub>2</sub> levels	389
11.3.5 Climatic effects of increasing CH <sub>4</sub> levels	391
11.3.6 Climatic effects of increasing CO levels	392
11.3.7 Climatic effects of increasing H <sub>2</sub> levels	393
11.3.8 Climatic effects of cloud-cover feedbacks	393
11.4 General circulation models	393
11.4.1 Types of climate models	395
11.4.2 Solar radiation transfer in GCMs	396
11.4.3 Terrestrial radiation transfer in GCMs	398
11.4.4 Surface albedo and emissivity in GCMs	398
11.5 GCM climate projections	399
11.5.1 SRES emission scenarios	400
11.5.2 Global change in temperature	403
11.5.3 Global change in precipitation	404
11.5.4 Global change in sea level	406
11.6 Bibliography	410
11.6.1 Notes	410
11.6.2 References and further reading	410
<b>12 Planetary evolution and comparative climatology</b>	<b>413</b>
12.1 Introduction	413
12.1.1 Origin of the solar system	415
12.1.2 Evolution of planetary atmospheres	416
12.1.3 Escape processes	417
12.2 The evolution of the Earth's climate	419
12.2.1 The Precambrian atmosphere	420
12.2.2 The faint–young–Sun paradox	420

12.2.3 Greenhouse–weathering evolution model	421
12.2.4 Surface temperature and CO <sub>2</sub> evolution	426
12.3 Comparative climatology of the terrestrial planets	427
12.3.1 Mercury	427
12.3.2 Venus	428
12.3.3 Mars	434
12.4 The giant planets	438
12.5 Titan’s atmosphere and haze	439
12.5.1 Physical properties	442
12.5.2 Collisionally induced absorption	444
12.5.3 Geometric albedo	445
12.5.4 Laboratory and in-situ measurements	446
12.5.5 Haze formation	447
12.5.6 Thermal structure	453
12.5.7 Atmospheric chemistry	454
12.6 Extrasolar planets	460
12.7 Bibliography	461
12.7.1 Notes	461
12.7.2 References and further reading	461
<b>A Physical constants</b>	<b>467</b>
<b>B Tables of reactions</b>	<b>468</b>
<b>Index</b>	<b>477</b>