

Contents

Symbols and Units	page	xii
Symbols		xii
Units		xvii
Scientific Notation		xvii
Preface		xix
Acknowledgements		xxi
I Introduction		1
1.1 Urban Ecology		2
1.1.1 Urban Ecosystems		2
1.1.2 Urban Metabolism		3
1.1.3 Urban vs Rural		4
1.2 Environmental Impacts of Urban Development		5
1.2.1 Urban Pedosphere and Lithosphere		5
1.2.2 Urban Hydrosphere		5
1.2.3 Urban Biosphere		5
1.2.4 Urban Atmosphere		6
1.3 Urbanization and Urban Form		6
1.3.1 First Phase of Urbanization		7
1.3.2 Second Phase of Urbanization		9
1.3.3 Future Urbanization Pathways		10
1.4 Planning for More Sustainable Cities		10
1.4.1 Renewable and Nonrenewable Resources		10
1.4.2 The Ecological Footprint of Cities		10
1.4.3 Planning for More Sustainable and Resilient Cities		12
Summary		13
2 Concepts		14
2.1 The Urban 'Surface'		15
2.1.1 Defining the Land-Atmosphere Interface in Cities		15
2.1.2 The Hierarchy of Urban Units		18
2.1.3 Description of Urban Surface Properties		20
2.1.4 Classification of the Urban Surface		25
2.2 The Urban Atmosphere		29
2.2.1 Scales of Urban Climate Phenomena		29
2.2.2 The Vertical Structure of the Urban Atmosphere		30
2.2.3 Linking the Vertical Structure to Horizontal Scales		34
2.3 Defining an Urban Climate		35
2.3.1 The Superposition of Urban and Non-Urban Influences on Climate		35
2.3.2 Dealing with the Complexity of the Urban System		36
2.3.3 Isolating Urban Effects		38
2.3.4 Identifying Causes of Urban Effects		40
2.3.5 Transferability of Results and Answers		42
Summary		42

3	Methods	44
3.1	Field Observations	45
3.1.1	Instruments and Their Exposure	46
3.1.2	Measurements at Fixed Stations	52
3.1.3	Mobile Measurements	55
3.1.4	Flow-Following Techniques	58
3.1.5	Remote-Sensing Techniques	59
3.2	Physical Modelling	60
3.2.1	Scaling and Similitude	60
3.2.2	Laboratory Models	61
3.2.3	Outdoor Scale Models	63
3.3	Numerical Modelling	66
3.3.1	Governing Equations	66
3.3.2	Numerical Experimental Design	69
3.3.3	Micro- and Local-Scale Urban Climate Models	71
3.3.4	Mesoscale Urban Models	72
3.4	Empirical Models	74
	Summary	75
4	Airflow	77
4.1	Basics of Wind and Turbulence	78
4.1.1	Mean and Turbulent Parts	78
4.1.2	Production of Turbulence	80
4.1.3	Dissipation of Turbulence	81
4.2	Flow in the Roughness Sublayer	82
4.2.1	Isolated Buildings	82
4.2.2	Uniform Building Arrays	86
4.2.3	Streets and Intersections	89
4.2.4	Arrays with Uneven Heights and Tall Buildings	93
4.2.5	Spatially Averaged Flow and Turbulence Statistics	95
4.3	Flow in the Inertial Sublayer	98
4.3.1	The Profile of Mean Wind	99
4.3.2	Urban Surface Roughness	102
4.3.3	Turbulence and Turbulent Exchange	105
4.3.4	Local-Scale Advection	107
4.4	Flow in the Mixed Layer	109
4.4.1	Roughness Influences	109
4.4.2	Thermal Influences	114
4.4.3	Combined Roughness and Thermal Influences	118
	Summary	120
5	Radiation	122
5.1	Basics of Radiation Exchanges and Budgets	123
5.1.1	Basic Radiation Principles and Laws	123
5.1.2	Radiation-Mass Interactions	124
5.1.3	The Surface Radiation Budget	126
5.2	Radiation in the Urban Canopy Layer	128
5.2.1	Radiation Properties of the Urban Canopy	128
5.2.2	Isolated Buildings	132

5.2.3	Urban Canyon	134
5.2.4	Albedo and Emissivity of Urban Systems	140
5.3	Radiation in the Urban Boundary Layer	145
5.3.1	Urban Aerosol	145
5.3.2	Shortwave Radiation	146
5.3.3	Longwave Radiation	150
5.4	Surface Net Allwave Radiation Budget	151
5.4.1	Urban–Rural Differences of Net Radiation	151
	Summary	154
6	Energy Balance	156
6.1	Basics of Energy Transfer and Balance	157
6.1.1	Energy Balance of a Flat Surface	157
6.1.2	Energy Balance of Urban Systems and Elements	158
6.1.3	Case Studies	159
6.2	Anthropogenic Heat Flux	160
6.2.1	Estimating the Anthropogenic Heat Flux	162
6.2.2	Controls on Anthropogenic Heat Flux	164
6.2.3	Significance of Anthropogenic Heat Flux	166
6.3	Heat Storage Change	168
6.3.1	Controls on Heat Storage Change	168
6.3.2	Estimating and Modelling Urban Heat Storage Change	171
6.3.3	Typical Values of Urban Heat Storage Change	174
6.4	Turbulent Heat Fluxes	175
6.4.1	Modelling Turbulent Heat Transfer	176
6.4.2	Measurement of Turbulent Heat Fluxes	178
6.4.3	Controls on Turbulent Heat Fluxes	180
6.5	Example Energy Balances in Cities	184
6.5.1	Energy Balance of Individual Facets	184
6.5.2	Energy Balance of Buildings	187
6.5.3	Energy Balance of Urban Canyons	187
6.5.4	Energy Balance of an Urban Canopy	190
6.5.5	Urban–Rural Energy Balance Differences	193
	Summary	195
7	Urban Heat Island	197
7.1	Urban Temperatures and Heat Island Types	198
7.1.1	Surface Temperatures	200
7.1.2	Air Temperatures	202
7.1.3	Subsurface Temperatures	205
7.1.4	Heat Island Magnitude	205
7.2	Surface Heat Island	206
7.2.1	Observation	206
7.2.2	Spatial and Temporal Variability	206
7.2.3	Genesis of Surface Heat Islands	210
7.3	Canopy Layer Heat Island	213
7.3.1	Observation	213
7.3.2	Spatial Morphology	213
7.3.3	Maximum Canopy Layer Heat Island	215
7.3.4	Diurnal Variations	216

	7.3.5	Effects of Weather and Surface State	218
	7.3.6	Seasonal Variations	222
	7.3.7	Genesis of Canopy Heat Islands	223
	7.3.8	Final Remarks	226
	7.4	Boundary Layer Heat Island	226
	7.4.1	Spatial Structure	228
	7.4.2	Variability	232
	7.4.3	Genesis of Boundary Layer Heat Islands	233
	7.5	Subsurface Heat Island	234
	7.5.1	Genesis of Subsurface Heat Islands	236
		Summary	236
8	Water		238
	8.1	Basics of Surface Hydrology and Water Balances	239
	8.1.1	Hydrologic Cycle	239
	8.1.2	The Surface Water Balance	239
	8.2	Water Balance of Urban Hydrologic Units	241
	8.2.1	Urban Development of River Catchments	241
	8.2.2	The Water Balance of an Urban Catchment	241
	8.2.3	Water Balance of an Urban Neighbourhood	242
	8.2.4	Water Balance of an Entire City	242
	8.3	Urban Effects on Water Balance Components	243
	8.3.1	Precipitation	243
	8.3.2	Piped Water Supply	244
	8.3.3	Anthropogenic Water Vapour	247
	8.3.4	Evaporation	248
	8.3.5	Runoff	249
	8.3.6	Change in Storage	251
	8.3.7	Groundwater	252
	8.3.8	Advection	252
		Summary	253
9	Atmospheric Moisture		254
	9.1	Basics of Atmospheric Moisture	255
	9.1.1	Humidity	255
	9.1.2	Condensation	256
	9.2	Urban Effects on Humidity	257
	9.2.1	Urban Canopy Layer	257
	9.2.2	Urban Boundary Layer	262
	9.2.3	Genesis of Effects	264
	9.3	Urban Effects on Condensation	264
	9.3.1	Dew	264
	9.3.2	Fog	265
		Summary	268
10	Clouds and Precipitation		270
	10.1	Basics of Cloud and Precipitation Formation	271
	10.1.1	Warm Cloud Processes	271
	10.1.2	Cold Cloud Processes	272
	10.1.3	Thunderstorms	272

10.2	The Methodological Challenge	273
10.2.1	The Discrete Nature of Cloud and Precipitation	273
10.2.2	Observing Cloud and Precipitation	273
10.3	Urban Observations	275
10.3.1	Clouds	275
10.3.2	Precipitation	276
10.3.3	Snowfall and Freezing Rain	279
10.4	Hypotheses of Urban Effects	281
10.4.1	Modification of Moisture and Thermodynamic Processes	282
10.4.2	Modification of Dynamical Processes	286
10.4.3	Modification of Microphysical Processes	288
	Summary	292
11	Air Pollution	294
11.1	Basics of Air Pollution	295
11.1.1	Emissions	298
11.1.2	Dispersion and Transport	299
11.1.3	Removal and Transformation	301
11.1.4	Scales of Air Pollution	302
11.2	Micro- and Local-Scale Air Pollution in Cities	303
11.2.1	Indoor Air Pollution	304
11.2.2	Outdoor Air Pollution in the Urban Canopy Layer	307
11.2.3	Air Pollution from Elevated Point Sources	312
11.3	Urban-Scale Air Pollution	315
11.3.1	Meteorological Controls on Air Quality in the Urban Boundary Layer	315
11.3.2	Smog	316
11.3.3	Modelling Urban Air Pollution	322
11.4	Regional and Global Effects of Urban Air Pollution	325
11.4.1	Urban Plumes	325
11.4.2	Effects of Urban Pollutants on Ecosystems Downwind	328
	Summary	330
12	Geographical Controls	332
12.1	The Macroclimatic Context of Cities	333
12.1.1	Urban Population and Macroclimates	333
12.1.2	Urban Effects in Different Macroclimates	339
12.1.3	The Urban Surface Energy Balance in Different Macroclimates	339
12.1.4	The Urban Heat Island in Different Macroclimates	341
12.2	Topography	342
12.2.1	Cities Affected by the Mechanical Influences of Orography on Airflow	344
12.2.2	Cities Affected by the Thermal Influences of Orography on Airflow	347
12.2.3	Cities Affected by Coastal Wind Systems	350
12.2.4	City Airflow in Diverse Topography	353
12.3	Synoptic Controls	353
12.3.1	Storm Systems	355
12.3.2	Floods	357
12.3.3	Heatwaves	358
	Summary	359

13	Cities and Global Climate Change	360
13.1	Urban Impacts on the Global Climate System	361
13.1.1	Land-Cover Change	361
13.1.2	Greenhouse Gases	362
13.2	Greenhouse Gas Emissions From Cities	365
13.2.1	Tracking Carbon in Cities	365
13.2.2	Directly Measuring Greenhouse Gas Emissions from Cities	370
13.2.3	Urban Land Cover and Greenhouse Gas Exchange	374
13.3	Global Climate Change in Urban Environments	376
13.3.1	Monitoring Climate Change in Urban Environments	377
13.3.2	Projecting Future Climates in Cities	378
13.3.3	Impacts of Global Climate Change on Cities	379
	Summary	383
14	Climates of Humans	385
14.1	Basics	386
14.1.1	Managing Heat	386
14.1.2	Maintaining Postural Balance	386
14.2	The Human Energy Balance	387
14.2.1	Internal Energy Exchanges	387
14.2.2	External Energy Exchanges	388
14.2.3	The Radiation Budget	389
14.2.4	Sensible Heat Flux	391
14.2.5	Latent Heat Flux	392
14.2.6	Clothing	393
14.3	Thermal Stress and Body Strain	394
14.4	Thermal Comfort and Its Assessment	395
14.4.1	Indoors	396
14.4.2	Outdoors	397
14.4.3	Thermal Indices	400
14.5	Wind and Comfort	401
14.6	The Urban Effect on Human Climates	402
14.6.1	Microclimates	402
14.6.2	Neighbourhood	404
14.6.3	Urban Scale	406
14.7	Indoor Climates	406
	Summary	407
15	Climate-Sensitive Design	408
15.1	Basics of Climate-Sensitive Planning and Design	409
15.1.1	Political Context and Policy Mechanisms	409
15.1.2	Climate Assessments	410
15.1.3	Guiding Principles	411
15.2	Design Interventions at Different Scales	418
15.2.1	Cities	419
15.2.2	Neighbourhoods	423
15.2.3	Facets	424
15.2.4	Buildings	427
15.2.5	Streets and Urban Blocks	431

15.2.6	Trees	433
15.2.7	Gardens and Parks	438
15.2.8	Water as a Design Feature	439
15.3	The Well-Planned and Designed City	441
15.3.1	Resource Use	444
15.3.2	Comfort	444
15.3.3	Air Quality	446
15.3.4	Weather Extremes	448
	Summary	451
	Epilogue	453
A1	History of Urban Climatology	454
A1.1	Pioneer Urban Climatographies (Prior to 1930)	454
A1.2	Advances in Micro- and Local Climatology (1930 to 1965)	455
A1.3	Towards a Physical Climatology of Cities (1965 to 2000)	457
A1.4	Consolidation and Prediction (Since 2000)	459
A2	Site Codes and Data Sources	460
A3	Glossary and Acronyms	469
	References	486
	Subject Index	510
	Geographical Index	520