

Studies in Wind Engineering and Industrial Aerodynamics, Vol. 1

Engineering meteorology

E. Plate (Editor)



Elsevier

Studies in Wind Engineering and Industrial Aerodynamics, 1

Engineering meteorology

**Fundamentals of Meteorology and Their Application to Problems in
Environmental and Civil Engineering**

edited by

ERICH J. PLATE

Institut Wasserbau III, Universität Karlsruhe, Karlsruhe, West Germany



ELSEVIER SCIENTIFIC PUBLISHING COMPANY
Amsterdam — Oxford — New York

1982

CONTENTS

Preface	v
List of Contributors	ix
List of symbols	xxi
Abbreviations	xxxi

PART I: FUNDAMENTALS

Chapter 1: The atmosphere	1
by H.A. Panofsky	
1.1. Introduction	1
1.2. Composition of the atmosphere	2
1.3. Average vertical structure	4
1.4. Meteorological variables	5
1.4.1. Temperature	5
1.4.2. Atmospheric pressure	6
1.4.3. Atmospheric humidity	7
1.4.4. Air density	9
1.4.5. Vertical velocity	9
1.4.6. Horizontal winds	9
1.4.7. Coverage of meteorological observations	10
1.5. The meteorological equations	11
1.5.1. Scale considerations	11
1.5.2. The gas law	12
1.5.3. The moisture equation	13
1.5.4. The first law of thermodynamics	14
1.5.5. The vertical equation of motion	15
1.5.6. The horizontal equation of motion (wind equation)	17
1.5.7. Other equations and variables	21
1.6. Characteristics of atmospheric motions	22
1.6.1. Climate and global circulation systems	22
1.6.2. Weather-map scale systems	24
1.6.3. Mesoscale systems	29
1.6.4. Microscale circulations	30
References	32
Chapter 2: Radiation and the radiation budget of the atmosphere	33
by K. Bullrich	
2.1. Introduction	33
2.2. Average radiation conditions of the atmosphere	33
2.2.1. The radiation spectrum	34
2.2.2. Directionality of radiation	35
2.2.3. Radiation balances: average conditions	36

2.3. Solar radiation ($0.29 < \lambda \lesssim 3 \mu\text{m}$)	40
2.3.1. The extraterrestrial solar radiation	40
2.3.2. Balance of radiation at the outer edge of the atmosphere	42
2.4. Short wave radiation	44
2.4.1. Atmospheric composition and its effect on radiation	44
2.4.2. The direct solar radiation R_{sd} reaching the ground	49
2.4.3. Global radiation received at the earth's surface	53
2.4.4. Short wave reflection	56
2.5. Long-wave (terrestrial) radiation (wave lengths $\lambda > 3 \mu\text{m}$)	58
2.5.1. Radiation laws	58
2.5.2. Effective terrestrial radiation in the long-wave spectral range at the earth's surface	59
2.6. Budgets of radiational energy	63
2.6.1. Radiation budgets over the height of the atmosphere	63
2.6.2. Radiation budget at the ground level	65
2.6.3. Man-made modification of the radiation budget	68
References	69
 Chapter 3: Cloud and precipitation physics and the water budget of the atmosphere	71
by H.R. Pruppacher	
3.1. The water budget of the atmosphere	71
3.1.1. The significance of water substance	71
3.1.2. The cycle of water substance in the atmosphere	72
3.2. Cloud and precipitation physics: Introduction	81
3.3. Cooling processes in the atmosphere	83
3.4. The atmospheric aerosol	88
3.5. Phase change	97
3.6. Growth of cloud particles	104
3.6.1. Diffusional growth and evaporation	104
3.6.2. Growth by collision	110
3.7. Electrical effects	119
References	122
 Chapter 4: Global climatology	125
by A. Baumgartner, G. Enders, M. Kirchner and H. Mayer	
4.1. Introduction	125
4.1.1. Elements of climatology	126
4.1.2. Statistical representation of climatological variables	128
4.1.3. Graphical representation of climatological data	129
4.1.4. Sources of climatological information	129
4.2. Radiation and energy	129
4.2.1. Introduction	129
4.2.2. Global distribution of radiation parameters	130
4.2.3. Global distribution of heat fluxes	135

4.3. Temperatures	137
4.3.1. Introduction	137
4.3.2. Diurnal and annual variation of temperatures	138
4.3.3. Global distributions of temperatures	142
4.3.4. Global variability of temperatures	143
4.4. Atmospheric humidity and precipitation	146
4.4.1. Introduction	146
4.4.2. Diurnal and annual variation of the vapour pressure	148
4.4.3. Global distribution of atmospheric humidity	149
4.4.4. Global distribution of cloudiness and fog	152
4.4.5. Global distribution of precipitation	153
4.4.6. Global distribution of the monthly enthalpy	155
4.5. Wind and pressure fields	158
4.5.1. Introduction	158
4.5.2. Diurnal and annual variation of atmospheric pressure and wind velocity	159
4.5.3. Global distribution of pressure and wind	163
4.5.4. Atmospheric and oceanic motions	165
4.6. Classification of climates	166
4.7. Topoclimatology	169
4.7.1. Introduction	169
4.7.2. The climate of slopes	169
4.7.3. The climate of valleys	173
4.7.4. The climate of mountains	173
4.8. Climatic fluctuations	174
4.8.1. Natural causes of climatic fluctuations	175
4.8.2. Man's influence on climate	175
References	176
Chapter 5: Atmospheric turbulence	179
by N.O. Jensen and N.E. Busch	
5.1. Introduction	179
5.1.1. Turbulence in the atmospheric boundary layer	179
5.2. Equations of motion	181
5.2.1. Fundamental equations	181
5.2.2. Reynolds approach	183
5.2.3. Equations for the turbulent flux terms	184
5.3. Analysis of averaged quantities	186
5.3.1. Dimensional analysis	186
5.3.2. Asymptotic scaling	189
5.3.3. Boundary layer scaling	192
5.4. Variance budgets	193
5.4.1. The turbulent energy equation	193
5.4.2. Turbulent energy budgets	194
5.4.3. Turbulence equations for scalars	196

5.5.	Analysis of spectral quantities	197
5.5.1.	Spectral definitions	197
5.5.2.	The Kolmogorov range	200
5.5.3.	The Taylor hypothesis	202
5.6.	Variance spectra	203
5.6.1.	Power spectra of velocity	204
5.6.2.	Effect fof stability: Monin-Obukhov scaling	205
5.6.3.	Unstable conditions: mixed layer scaling	209
5.6.4.	Spectra of scalers	210
5.6.5.	Co-spectra	211
5.7.	Probability distributions of turbulence	213
5.7.1.	Intermittency, Kolmogorov's revised hypothesis	213
5.7.2.	Exceedance statistics	215
5.7.3.	Empirical simulation of turbulence	218
5.8.	Spatial and temporal variability of atmospheric turbulence	220
5.8.1.	Inhomogeneity	221
5.8.2.	Non-stationarity	224
5.8.3.	Two-point statistics	226
5.9.	Concluding remarks	229
	References	229
Chapter 6: Atmospheric boundary layers over homogeneous terrain		233
by S.P. Arya		
6.1.	Introduction and some definitions	233
6.1.1.	Definition of the ABL	233
6.1.2.	Depth of the ABL	234
6.1.3.	The surface layer	236
6.2.	Factors influencing the ABL structure	237
6.3.	Surface-layer similarity theories and observations	238
6.3.1.	The logarithmic profile law for a neutral surface layer	238
6.3.2.	The free convection similarity theory	240
6.3.3.	The Monin-Obukhov similarity theory	241
6.4.	Outer-layer similarity theories	246
6.4.1.	The Rossby-number similarity theory	246
6.4.2.	Deardorff's similarity theory	247
6.4.3.	The free convection similarity theory	247
6.5.	Observations of the outer layer	248
6.5.1.	Convective regime ($h/L \leq 5$)	248
6.5.2.	Unstable regime ($-5 < h/L < -0.2$)	252
6.5.3.	Near-neutral regime ($-0.2 \leq h/L \leq 0.2$)	253
6.5.4.	Stable-continuous regime ($0.2 < h/L < 2$)	254
6.5.5.	Stable-sporadic regime ($h/L \geq 2$)	256
6.6.	Diurnal variations in the ABL over land	257
6.6.1.	Some qualitative aspects	257
6.6.2.	Variations of $\bar{\theta}$, and h	260

6.6.3. Diurnal wind variations	260
6.7. Numerical modelling of the ABL	262
6.7.1. Specification of K	262
6.7.2. Higher-order closure models	264
6.7.3. Large-eddy simulation models	265
Acknowledgement	266
References	266
Chapter 7: Atmospheric boundary layers over non-homogeneous terrain	269
by J.C.R. Hunt and J.E. Simpson	
7.1. Introduction	269
7.2. General response of the boundary layer to a weak change in surface conditions	270
7.2.1. One-dimensional change in surface conditions	270
7.2.2. Changes in surface conditions over a limited area	272
7.2.3. Equations for perturbed shear layers	273
7.3. Change of roughness	275
7.3.1. Short range effects	275
7.3.2. Long range effects of roughness changes ($x \sim G/f$)	281
7.3.3. Area roughness	282
7.4. Change of surface temperature	285
7.4.1. Brief survey of steady surface temperature changes	285
7.4.2. Change of surface temperature and the sea breeze	287
7.5. Change of surface elevation	292
7.5.1. Neutrally stable approach flow	292
7.5.2. Stably stratified flow over hills	308
7.6. Heating and cooling effects	313
Acknowledgement	314
References	314

PART II: APPLICATIONS

Chapter 8: Exchange processes at the earth-atmosphere interface	319
by W. Brutsaert	
8.1. Introduction	319
8.1.1. The interfacial energy budget	319
8.1.2. The hydrological cycle	320
8.1.3. Transport of other admixtures	321
8.1.4. Vertical transport above uniform surface; fetch requirements .	322
8.2. Direct or eddy-correlation methods	323
8.3. Mean-concentration profile methods for any admixture	324
8.3.1. Mean profile equations and related bulk transfer coefficients .	325
8.3.2. Roughness length for a scalar; surface resistances	331
8.4. Energy budget methods	342
8.4.1. Standard procedures	344

8.4.2. Energy budget methods for potential evaporation	347
8.4.3. Energy budget under conditions of water shortage.	352
8.5. Effects of local (atmospheric) advection)	356
8.5.1. Some methods of determining lake evaporation.	356
8.5.2. Some studies of oasis effects on evapotranspiration	362
References.	364
 Chapter 9: Precipitation evaluation in hydrology.	371
by J.F. Miller	
9.1. Introduction	371
9.1.1. Scope of chapter	371
9.1.2. Hydrologic design problems.	372
9.2. Precipitation observations.	373
9.2.1. Precipitation measurement.	373
9.2.2. Spatial and temporal distribution of precipitation	376
9.3. Probable maximum precipitation	379
9.3.1. Introduction.	379
9.3.2. PMP-estimates for non-orographic regions	382
9.3.3. PMP-estimates for orographic regions.	394
9.3.4. Seasonal variation of PMP	404
9.3.5. Statistical estimates of PMP	405
9.4. Precipitation frequency analysis	407
9.4.1. Introduction.	407
9.4.2. Basic data.	407
9.4.3. Graphical methods and plotting positions	408
9.4.4. Probability distributions.	409
9.4.5. Station data analysis.	410
9.4.6. Generalized charts	411
9.4.7. Estimates in regions of limited data	420
9.4.8. Within storms versus among storms	420
9.4.9. Season of occurrence	421
9.5. Precipitation aspects of design.	422
9.5.1. Urban drainage.	422
9.5.2. Reservoirs.	423
References.	424
 Chapter 10: Turbulent diffusion: chimneys and cooling towers	429
by S.R. Hanna	
10.1. Introduction	429
10.2. Review of diffusion theories	430
10.2.1. Statistical theory	430
10.2.2. Lagrangian similarity theory.	434
10.2.3. Gradient transport (K) theory	438
10.3. Gaussian plume model.	441
10.3.1. Development of model	441

10.3.2. Specifying σ_y and σ_z curves	442
10.3.3. Revisions to σ_y and σ_z curves	445
10.3.4. Stability classification	447
10.4. Plume rise	448
10.5. High ground level concentrations from elevated point sources	449
10.5.1. Peak to mean concentration ratios	449
10.5.2. Fumigation	451
10.6. Process emissions — small stacks and building effects	452
10.7. Removal	454
10.7.1. Dry deposition	454
10.7.2. Precipitation scavenging	455
10.7.3. Chemical reactions	456
10.8. Plume diffusion in special terrain	456
10.9. Cooling tower plumes	458
10.9.1. Plume rise of moist plumes	459
10.9.2. Condensation in the plume	462
10.9.3. Drift deposition calculations	466
10.10. Line and area sources	471
10.11. Regional diffusion models	474
Acknowledgements	474
References	474
 Chapter 11: Turbulent diffusion near buildings	481
by R.N. Meroney	
11.1. Introduction	481
11.1.1. Isolated versus collection of buildings	482
11.1.2. Flow structure around an isolated building	483
11.1.3. Influence of source location	485
11.1.4. Influence of receptor location	486
11.1.5. Special cases	487
11.2. Diffusion near an isolated structure	487
11.2.1. Aerodynamic downwash conditions	488
11.2.2. Dispersion enhancement models	490
11.2.3. Building surface to building transport	493
11.2.4. Peak-to-mean concentrations in building wakes	497
11.2.5. Worked example: SO ₂ from a petroleum refinery	501
11.3. Diffusion near a collection of buildings	502
11.3.1. Isolated building complex	502
11.3.2. Influence of downwind and upwind buildings or topography on turbulent diffusion	504
11.3.3. Windbreak or shelter influence on dispersion	508
11.3.4. Worked example: Odor dispersal	510
11.4. Transportation and associated diffusion problems	511
11.4.1. Gaseous pollutants in city street canyons	512
11.4.2. Gaseous pollutants exhausting from parking lot garages	516

11.5. Dispersion of dense or cold gas plumes	516
11.5.1. The fluid physics of dense plume behavior	516
11.5.2. Dense plume dynamics associated with structures, ground level release	518
11.5.3. Dense plume dynamics associated with structures — elevated releases	519
References	521
 Chapter 12: The interaction of wind and structures	527
by A.G. Davenport	
12.1. Introduction	527
12.2. Early estimates of wind forces	527
12.3. Tacoma narrows and after	534
12.4. A contemporary view of wind loading	536
12.5. Wind climate	537
12.5.1. Extreme winds based on surface wind measurements	538
12.5.2. Extreme winds based on gradient winds	539
12.5.3. Extreme winds in hurricanes	541
12.5.4. Extreme winds for thunderstorms and tornadoes	543
12.6. Effects of terrain and topography	543
12.6.1. The mean windspeed profile	545
12.6.2. Turbulence	550
12.7. Aerodynamic forces and responses	551
12.7.1. Aerodynamic pressures and forces: definitions and codified results	552
12.7.2. Structural responses	560
12.7.3. Wind in pedestrian areas	565
12.8. The prediction of risk	567
References	569
 Chapter 13: Wind tunnel modelling of wind effects in engineering	573
by E.J. Plate	
13.1. Introduction	573
13.2. Wind tunnel modelling of the atmosphere	575
13.2.1. General modelling criteria	575
13.2.2. Modelling of the atmospheric boundary layer: neutral stability	578
13.2.3. Modelling of the atmospheric boundary layer: laboratory equipment	589
13.2.4. Modelling of the atmospheric boundary layer: stratified flows	593
13.2.5. General remarks on near field and far field modelling	597
13.3. Wind tunnel modelling of environmental problems	598
13.3.1. General criteria for diffusion modelling	598
13.3.2. Modelling of local environmental problems	604

13.3.3. Modelling of mesoscale environmental problems	608
13.3.4. Environmental modelling and meteorological variability	612
13.4. Modelling of aerodynamic forces on structures	613
13.4.1. Modelling of pressures	615
13.4.2. Mean force modelling	618
13.4.3. Modelling of dynamic responses of structures to wind	624
13.4.4. Response of structures in natural environments	635
References	636
 Chapter 14: Ice problems in engineering	641
by J. Schwarz	
14.1. Introduction	641
14.2. Types of ice	641
14.3. Physical properties of ice	646
14.3.1. Density	646
14.3.2. Thermal conductivity	647
14.3.3. Thermal diffusivity	649
14.3.4. Electromagnetic properties	650
14.4. Mechanical properties	651
14.4.1. General	651
14.4.2. Compressive strength	651
14.4.3. Tensile strength	656
14.4.4. Flexural strength	658
14.4.5. Shear strength	661
14.4.6. Elastic modulus	661
14.4.7. Three-dimensional strength	663
14.5. Ice conditions	664
14.5.1. Ice terminology	664
14.5.2. Ice code	667
14.5.3. Areas of different ice conditions	667
14.5.4. Ice conditions	668
14.6. Application for engineering activities	670
14.6.1. Ice forces on structures	670
14.6.2. Icebreaking by ships	674
References	678
 Chapter 15: Wind wave problems in engineering	683
by H. Mitsuyasu	
15.1. Introduction	683
15.2. Wind waves	683
15.2.1. Generation of wind waves	684
15.2.2. The probability structure of wind waves	685
15.2.3. Wave spectra and their growth due to wind	691
15.2.4. Wave prediction based on empirical relationships	703
15.3. Wave breaking and spray formation	706
15.4. Storm surge and wind set-up	715

15.5. Interactions between waves and structures	720
15.5.1. Wave pressure upon a vertical wall	720
15.5.2. Wave force on a circular cylinder	722
Acknowledgements	725
References	725
Subject Index	731