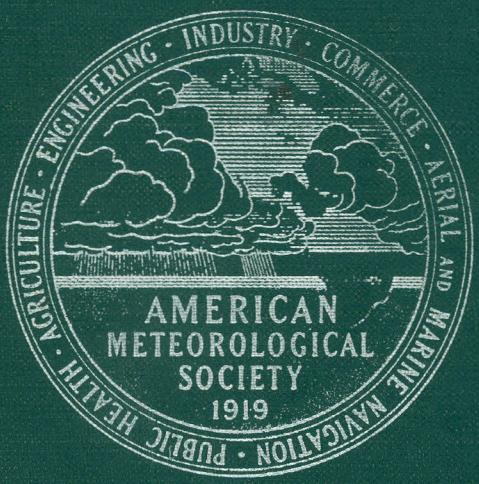
WORKSHOP on MICROMETEOROLOGY

DUANE A. HAUGEN, EDITOR



[redacted]

American Meteorological Society

Workshop on Micrometeorology

Niels E. Busch
Joost A. Businger
James W. Deardorff
Coleman duP. Donaldson
M. A. Estoque
Hans A. Panofsky
H. Tennekes
John C. Wyngaard

Edited by: Duane A. Haugen
Air Force Cambridge Research Laboratories

Published by the American Meteorological Society

Table of Contents

PREFACE

CHAPTER 1: ON THE MECHANICS OF ATMOSPHERIC TURBULENCE—NIELS E. BUSCH

1.1. Introduction 1
1.2. Equations of motion 2
1.3. Equations for the mean flow 6
1.4. Reynolds number similarity 16
1.5. Equations for the fluctuating flow: The closure problem 17
1.6. Energy budgets 19
1.7. Correction for moisture 21
1.8. Turbulence spectra: The hypothesis of universal equilibrium 23
1.9. Concluding remarks 27
Appendix: The Surface Boundary Layer (A Review of Recent Experimental Work) 28
1.A1. Flux-profile relationships 29
1.A2. Spectra of velocity, temperature and humidity 34
a. Spectra of vertical velocity 36
b. Spectra of longitudinal velocity 39
c. Spectra of lateral velocity 41
d. Ratios of spectra 42
e. Summary of velocity spectra 43
f. Spectra of temperature 44
g. Spectra of humidity 46
h. Cospectra of velocities, temperature and humidity 46
1.A3. Integral statistics 48
1.A4. Energy, variance, stress, and heat-flux budgets 50
1.A5. Local isotropy and the inertial subrange 52
List of Symbols 55
Text References 60
Appendix References 61

CHAPTER 2: TURBULENT TRANSFER IN THE ATMOSPHERIC SURFACE LAYER—JOOST A. BUSINGER

2.1. Introduction 67
2.2. The neutral case 69
a. The logarithmic profile 69
b. The von Kármán constant 71
c. Aerodynamic smooth flow 72
2.3. The diabatic case 73
a. Formulation of a stability parameter 73
b. Flux-profile relationships 75
c. The functions Ri (ζ) and $\alpha(\zeta)$ 78
d. Free convection 80
e. The critical Richardson number 84
f. The consequences of Ri_{cr} 85
g. The interaction of turbulence with gravity waves 87
2.4. Techniques of determining the turbulent fluxes 87
a. Air-sea bulk transfer coefficients 87
b. Determinations of the heat and momentum flux 90
c. Evaporation and the fluxes of trace constituents 93
List of Symbols 97
References 98

CHAPTER 3: ON SURFACE LAYER TURBULENCE—JOHN C. WYNGAARD

3.1. Introduction 101
3.2. The turbulent fluxes near the ground 103
3.3. Surface layer similarity 109
3.4. Asymptotic scaling 112
a. Local-free-convection scaling 112
b. Local-height-independent (z-less) stratification 119
3.5. Some dynamical aspects 121
a. Local free convection 121
b. Local z-less stratification 126
3.6. Spectral characteristics 128
3.7. Averaging times 135
3.8. The real surface layer 141
List of Symbols 146
References 148

CHAPTER 4: TOWER MICROMETEOROLOGY—HANS A. PANOFSKY

4.1. Introduction 151
4.2. Wind profiles 152
a. Neutral conditions, homogeneous terrain 152
b. Homogeneous terrain, diabatic conditions 155
c. The neutral wind profile in changing terrain 158
4.3. Temperature profiles 162
a. Homogeneous terrain 162
b. Heterogeneous terrain 163
4.4. Variances of velocity components 164
a. The energy budget 164
b. Variance of vertical velocity 164
c. Horizontal velocity components 165
4.5. Spectra 167
a. High frequencies 167
b. General properties of spectra of vertical velocity and temperature 167
c. Spectra of the horizontal wind components 168
4.6. Cross spectra 169
a. Introduction 169
b. Cross spectra between different variables 170
c. Cross spectra between like variables 170
List of Symbols 173
References 174

CHAPTER 5: SIMILARITY LAWS AND SCALE RELATIONS IN PLANETARY BOUNDARY LAYERS—H. TENNEKES

5.1. Introduction 177
5.2. Neutral barotropic boundary layers 178
a. Velocity-defect law 178
b. Law of the wall 182
c. The logarithmic wind profile 184
d. Scaling of other properties 187
e. Large eddies: Vortex rolls 189
5.3. The effects of buoyant heat transfer 193
a. Extension of the similarity laws 194
b. Free-convection scaling 196
c. Other scaling problems 205
d. Plumes and vortex rolls 209
5.4. Concluding remarks 211
List of Symbols 213
References 214

CHAPTER 6: NUMERICAL MODELING OF THE PLANETARY BOUNDARY LAYER—M. A. ESTOQUE

6.1. Introduction 217
6.2. Steady-state PBL over homogeneous terrain 219
6.3. Non-steady state PBL over homogeneous terrain 233
6.4. Steady-state PBL over nonhomogeneous terrain 241
6.5. Nonsteady-state PBL over nonhomogeneous terrain 255
a. One-dimensional nonhomogeneity 256
b. Two-dimensional nonhomogeneity 262
6.6. Concluding remarks 266
List of Symbols 267
References 268

CHAPTER 7: THREE-DIMENSIONAL NUMERICAL MODELING OF THE PLANETARY BOUNDARY LAYER—JAMES W. DEARDORFF

7.1. Introduction 271
7.2. The governing equations with grid-volume Reynolds averaging 273
7.3. Subgrid closure assumptions 275
a. Second-moment equations 276
b. Abbreviated theory with isotropic mean Reynolds stresses 284
c. Nonlinear eddy viscosity approach 285
7.4. Boundary conditions 287
a. Lateral 287
b. Upper 287
c. Lower 288
7.5. Finite-difference methods 290
a. The finite-difference grid 290
b. Nonlinear advection terms 292
c. Coriolis terms 292
d. Subgrid stresses 293
e. Poisson equation and pressure 293
f. Time differencing 294
g. Truncation error 295
h. Numerical program errors 298
i. Initial conditions 299
7.6. Results of 3-D numerical PBL studies 299
7.7. Retrospective comments 304
7.8. How should one view the boundary layer? 305
List of Symbols 307
References 309

CHAPTER 8: CONSTRUCTION OF A DYNAMIC MODEL OF THE PRODUCTION OF ATMOSPHERIC TURBULENCE AND THE DISPERSAL OF ATMOSPHERIC POLLUTANTS—COLEMAN duP. DONALDSON

8.1. Introduction 313
8.2. Equations for an atmospheric shear layer 315
8.3. Equations for turbulent shear layers 323
8.4. Selection of models 332
8.5. Search for model parameters 339
a. Application of model to free shear flows 344
b. Application of model to boundary layers 355
c. Some comments on second-order modeling techniques 358
8.6. An equation for the scale Λ_1 359
8.7. Relation of second-order models to K theory 361
8.8. Application of second-order modeling to the atmospheric boundary layer 375
8.9. Summary and conclusions 388
List of Symbols 389
References 390