

Alfred K. Blackadar

# Turbulence and Diffusion in the Atmosphere

Lectures  
in Environmental  
Sciences



Springer

Alfred K. Blackadar

# Turbulence and Diffusion in the Atmosphere

Lectures  
in Environmental Sciences

With 49 Figures  
and Two MS-DOS Program Diskettes

312/3900 INSTITUT  
FÜR METEOROLOGIE U. KLIMATOLOGIE  
UNIVERSITÄT HANNOVER  
HERRENHAUSER STR. 2 - 30119 HANNOVER



Springer

# Contents

<b>1</b>	<b>The Nature of Turbulence</b>	1
1.1	Two-Dimensional Eddies in the Atmosphere	2
1.2	The Reynolds Number and Its Significance	5
1.3	The Reynolds Approach to the Equations of a Turbulent Fluid	6
1.4	Averaging the Equation of Continuity	8
1.5	Fluxes and the General Conservation Equation	9
1.6	The Closure Problem	12
1.7	First-Order Closure – Exchange Theory	12
1.8	Problems	14
<b>2</b>	<b>The Navier–Stokes Equations</b>	17
2.1	The Nature of Stress	17
2.2	Invariants of Fluid Motions	18
2.3	The Navier–Stokes Equations	21
2.4	Reynolds Number Similarity	23
2.5	Averaging the Navier–Stokes Equations	23
2.6	Problems	25
<b>3</b>	<b>The Neutral Surface Boundary Layer</b>	27
3.1	Overview of the Atmospheric Boundary Layer	27
3.2	Wind Distribution in the Neutral Surface Layer	29
3.3	Mean Flow in the Vicinity of the Surface	34
3.4	Miscellaneous Topics	34
3.5	Distribution of Passive Mean Properties	36
3.6	Problems	38
<b>4</b>	<b>The Energy Equations of Turbulence</b>	41
4.1	Energy of the Instantaneous State of a Fluid	41
4.2	Work Done on the Boundary	42
4.3	Heat	44
4.4	The Energy Equations and Energy Transformations	45
4.5	The Second Law of Thermodynamics	46
4.6	The Boussinesq Approximation	47
4.7	Open Systems	48

4.8	Energy Transformations in a Turbulent System .....	50
4.9	Problems .....	52
<b>5</b>	<b>Diabatic Surface Boundary Layers .....</b>	<b>55</b>
5.1	Heat Flux in the Surface Layer .....	55
5.2	The Richardson Number and the Criterion of Turbulence .....	56
5.3	Wind Profile Similarity .....	58
5.4	Profiles of Mean Temperature .....	61
5.5	Some Useful Relationships .....	63
5.6	Problems .....	64
<b>6</b>	<b>Homogeneous Stationary Planetary Layers .....</b>	<b>67</b>
6.1	The Ekman Spiral .....	69
6.2	A Two-Layer Model of the PBL .....	73
6.3	Universal Wind Hodograph and the Resistance Laws .....	75
6.4	The Mixed Layer of the Ocean .....	79
6.5	Problems .....	80
<b>7</b>	<b>Unconstrained Boundary Layers .....</b>	<b>81</b>
7.1	Flow downwind of a Change of Roughness .....	81
7.2	Non-stationary Boundary Layers .....	83
7.3	The Surface Heat Balance Equation .....	83
7.4	Daytime Conditions in the PBL .....	86
7.5	The Planetary Boundary Layer at Night .....	89
7.6	Model Simulation of the PBL .....	94
7.7	Problems .....	96
<b>8</b>	<b>Statistical Representation of Turbulence I .....</b>	<b>99</b>
8.1	Scaling Statistical Variables in the PBL .....	101
8.2	Vertical Distributions of the Variances .....	103
8.3	Problems .....	107
<b>9</b>	<b>Statistical Representation of Turbulence II .....</b>	<b>109</b>
9.1	Spectrum and Cross Spectrum of Turbulence .....	109
9.2	Spatial Representation of Turbulence .....	111
9.3	The Equilibrium Theory of Turbulence .....	112
9.4	The Inertial Subrange .....	113
9.5	Surface Layer Velocity Component Spectra .....	114
9.6	Mixed Layer Velocity Component Spectra .....	116
9.7	Spectra of Scalar Quantities Including Temperature .....	118
9.8	Cospectra and Quadrature Spectra .....	118
9.9	Problems .....	120

<b>10 Turbulent Diffusion from Discrete Sources</b> .....	123
10.1 Morphology of Smoke Plumes .....	123
10.2 Continuity Principles .....	125
10.3 Fickian Diffusion .....	127
10.4 The Gaussian Distribution Function .....	130
10.5 Taylor's Diffusion Equation .....	131
10.6 Spectral Representation of Taylor's Equation .....	133
10.7 Stability Parameters .....	134
10.8 Gaussian Plume Models .....	136
10.9 Estimations Based on Taylor's Equation .....	140
10.10 Monte Carlo Models .....	143
10.11 Instantaneous Point Sources .....	144
10.12 Problems .....	146
<b>Appendix A. Derivation of the Turbulent Energy Equations</b> .....	147
A.1 Equations for the Instantaneous Energy .....	147
A.2 The Equation of Mean Internal Energy .....	151
A.3 The Mean Total Kinetic Energy Equation .....	152
A.4 The Equation for the Energy of Mean Motion .....	152
A.5 The Turbulent Kinetic Energy Equation .....	153
<b>Appendix B. Dimensional Analysis and Scaling Principles</b> .....	155
B.1 Checking Equations for Errors .....	155
B.2 Inferring an Unknown Relationship .....	156
B.3 Turkey Eggs, Anybody? .....	157
B.4 Problems .....	159
<b>Appendix C. Matching Theory and the PBL Resistance Laws</b> .....	161
<b>Appendix D. Description</b>	
<b>of the Planetary Boundary Layer Simulation Model</b> .....	165
D.1 Architecture of the Model .....	166
D.2 Surface Boundary Condition .....	167
D.3 The Free Convection Closure Scheme .....	169
D.4 Treatment of Cloud Formation .....	170
D.5 Treatment of Infrared Radiation .....	170
<b>Appendix E. A Monte Carlo Smoke Plume Simulation</b> .....	173
<b>References</b> .....	177
<b>Index</b> .....	181