

ATMOSPHERIC PROCESSES OVER COMPLEX TERRAIN

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William Blumen

Editor

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William Blumen
Editor

American Meteorological Society
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PREFACE

A workshop on atmospheric processes over complex terrain, sponsored by the American Meteorological Society, was convened in Park City, Utah from 24–28 October 1988. The overall objective of the workshop was one of interaction and synthesis—interaction among atmospheric scientists carrying out research on a variety of orographic flow problems, and a synthesis of their results and points of view into an assessment of the current status of topical research problems. The final day of the workshop was devoted to an open discussion on the research directions that could be anticipated in the next decade because of new and planned instrumentation and observational networks, the recent emphasis on development of mesoscale numerical models, and continual theoretical investigations of thermally forced flows, orographic waves, and stratified turbulence.

The Park City Workshop was planned by a program committee consisting of Bob Banta, Jan Paegle, Bill Blumen, Bill Clements, Sumner Barr, and Mike Fosberg. The workshop could not have taken place without generous grants from the following organizations, with the responsible individuals also indicated: the U.S. Forest Service (M. Fosberg), the U.S. Department of Energy (A. Patrinos), the U.S. Army Research Office (W. Bach), and the U.S.A.F. Office of Scientific Research (Lt Cols J. Koermer and J. Stobie). We also thank both the Rocky Mountain Forest and Range Experiment Station of the U.S. Forest Service (D. Fox) for arranging for the federal funds from

all sources to be transferred to the American Meteorological Society, and Joe Egger for contributing his illustrations of atmospheric processes over complex terrain to the workshop.

This monograph represents an outgrowth of the Park City Workshop. The authors have contributed chapters based on their lecture material. Workshop discussions indicated interest in both the remote sensing and predictability of orographic flows. These chapters were solicited following the workshop in order to provide a more balanced view of current progress and future directions in research on atmospheric processes over complex terrain. The timely publication of this monograph has been aided by additional grants from the U.S. Forest Service (M. Fosberg), the U.S. Department of Energy (A. Patrinos and H. Moses), the U.S. Army Research Office (W. Bach), the U.S.A.F. Office of Scientific Research (J. Stobie), and the Environmental Research Laboratories of the National Oceanic and Atmospheric Administration (NOAA/ERL).

Others have also provided important and timely contributions. Merlyn Holmes provided editorial assistance and Lynda McGinley was invaluable in keeping all of the editorial activities running smoothly. We thank both of them.

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TABLE OF CONTENTS

Preface	xii
List of Contributors	xiii
Chapter 1. Mountain Meteorology	
—WILLIAM BLUMEN	1
ABSTRACT	1
1.1 Introduction	1
1.2 Some historical footnotes	1
1.2.1 <i>Surface winds</i>	1
1.2.2 <i>Observations and observers</i>	2
1.2.3 <i>The discovery of atmospheric waves</i>	3
1.3 Current directions	3
<i>Acknowledgments</i>	4
Chapter 2. Observations of Thermally Developed Wind Systems in Mountainous Terrain	
—C. DAVID WHITEMAN	5
ABSTRACT	5
2.1 Introduction to diurnal mountain winds	5
2.1.1 <i>Summary of recent field experiments</i>	6
2.2 Along-valley wind systems	7
2.2.1 <i>Climatology</i>	7
2.2.2 <i>Basic physics</i>	9
2.2.2.1 TOPOGRAPHIC AMPLIFICATION FACTOR	9
2.2.2.2 EQUATIONS FOR THE VALLEY WIND SYSTEM	13
2.2.3 <i>Radiation and surface energy budgets</i>	14
2.2.3.1 RADIATION BUDGET	15
2.2.3.2 SURFACE ENERGY BUDGET	17
2.2.4 <i>Atmospheric budgets of mass, heat, momentum, and moisture</i>	21
2.2.4.1 CONSERVATION OF ATMOSPHERIC MASS	22
2.2.4.2 THERMAL ENERGY BUDGET	23
2.2.4.3 MOMENTUM BUDGET	25
2.2.4.4 HUMIDITY BUDGET	25
2.3 Slope wind systems	25
2.3.1 <i>Simple slope flows</i>	25
2.3.2 <i>Slope flows on valley sidewalls</i>	26
2.4 Morning transition	28
2.5 Evening transition	32
2.6 The diurnal cycle	34
2.7 Other phenomena	35
2.7.1 <i>Influence of external winds</i>	35
2.7.2 <i>Maloja winds</i>	36
2.7.3 <i>Jets at valley exits</i>	36
2.7.4 <i>Antiwind systems</i>	38
2.7.5 <i>Tributary flows</i>	38
2.8 Future research	39
<i>Acknowledgments</i>	42

Chapter 3. Thermally Forced Flows: Theory	
—JOSEPH EGGER	43
ABSTRACT	43
3.1 Introduction	43
3.2 The problem	43
3.3 Circulation in a cavity with differentially heated sidewalls	44
3.4 Sloping boundaries	48
3.5 Circulation in valley cross-sections	51
3.6 Toward three-dimensional modeling	53
3.7 Three-dimensional valley flow	55
3.8 Outlook	57
Chapter 4. Mountain Waves and Downslope Winds	
—DALE R. DURRAN	59
ABSTRACT	59
4.1 Introduction	59
4.2 Fundamentals of internal gravity waves	59
4.3 Application to small-amplitude mountain waves	62
4.3.1 <i>Sinusoidal ridges; constant wind speed and stability</i>	62
4.3.2 <i>Isolated mountain; constant wind speed and stability</i>	63
4.3.3 <i>Vertical variations in wind speed and stability</i>	65
4.4 Downslope windstorms	66
4.4.1 <i>Three explanations for the production of severe downslope winds</i>	66
4.4.2 <i>A comparison of the hydraulic and the vertically propagating wave theories</i>	69
4.4.3 <i>A comparison of the hydraulic and the wave-breaking mechanisms</i>	71
4.4.4 <i>Forecasting downslope winds</i>	74
4.4.5 <i>Gustiness near the surface in downslope winds</i>	76
4.5 Flow over isolated mountains	78
<i>Acknowledgments</i>	81
Chapter 5. Fluid Mechanics of Airflow over Hills: Turbulence, Fluxes, and Waves in the Boundary Layer	
—D. J. CARRUTHERS and J. C. R. HUNT	83
ABSTRACT	83
5.1 Introduction	83
5.1.1 <i>Overview</i>	83
5.1.2 <i>Classification of flow regimes</i>	84
5.1.2.1 STRATIFICATION EFFECTS	84
5.1.2.2 ROTATION EFFECTS	85
5.1.2.3 ROUGHNESS CHANGES	85
5.2 Modeling of turbulent airflow over hills	85
5.2.1 <i>Linear analysis</i>	86
5.2.1.1 GENERAL EQUATIONS	86
5.2.1.2 INNER REGION SOLUTION	86
5.2.1.3 MIDDLE LAYER SOLUTION	87
5.2.1.4 UPPER LAYER SOLUTION	87
5.2.1.5 SURFACE ROUGHNESS EFFECTS	88
5.3 Effects of stratification	88
5.3.1 <i>Uniform stratification</i>	89
5.3.2 <i>More complex stability profiles</i>	89

CONTENTS

5.3.3	<i>Elevated inversion above neutral boundary layer</i>	90
5.3.4	<i>Strong stratification; large aspect ratios</i>	91
5.4	Turbulence	91
5.5	Numerical models and flow over complex terrain	93
5.5.1	<i>Isolated hills</i>	93
5.5.2	<i>Complex terrain</i>	94
5.6	Dispersion and deposition over complex terrain	95
5.6.1	<i>Overview and key processes</i>	95
5.6.2	<i>Localized sources near hills</i>	96
5.6.2.1	IDEALIZED HILL SHAPE [EPA-CTDM MODEL (PAINE ET AL. 1987)]	98
5.6.2.2	FOURIER ANALYSIS OF HILL SHAPES	98
5.6.3	<i>Dispersion and deposition over terrain for well-mixed scalars</i>	98
5.6.4	<i>Temperature and humidity fields</i>	102
5.7	Discussion	103
	<i>Acknowledgments</i>	103
	APPENDIX: Why Can't Stably Stratified Air Rise over High Ground?	
	—RONALD B. SMITH	105
5.A.1	Introduction	105
5.A.2	Combining the hydrostatic and Bernoulli equations	105
5.A.3	Application	107
5.A.4	Conclusion	107
	<i>Acknowledgments</i>	107
Chapter 6. Rugged Terrain Effects on Diffusion		
	—STEVEN R. HANNA and DAVID G. STRIMAITIS	109
6.1	Introduction	109
6.1.1	<i>Problems</i>	109
6.1.2	<i>Overview of history of research</i>	110
6.2	Summary of EPA models and evaluations	111
6.2.1	<i>Model descriptions</i>	111
6.2.2	<i>Evaluations of regulatory models</i>	113
6.2.2.1	EPA EVALUATION AT LUKE MILL AND CINDER CONE BUTTE	113
6.2.2.2	EVALUATION OF COMPLEX I AND RTDM AT WIDOWS CREEK	114
6.3	Theories and experiments regarding diffusion over slopes and valleys	114
6.3.1	<i>Diffusion models for slope flows</i>	115
6.3.2	<i>Diffusion models for narrow valleys</i>	116
6.3.3	<i>DOE ASCOT experiments</i>	118
6.4	EPA Complex Terrain Model Development (CTMD) Program	121
6.4.1	<i>Objectives</i>	121
6.4.2	<i>Fluid modeling</i>	123
6.4.3	<i>Field experiments</i>	125
6.4.3.1	CINDER CONE BUTTE	126
6.4.3.2	HOGBACK RIDGE	127
6.4.3.3	TRACY POWER PLANT	127
6.4.4	<i>Assumptions contained in the Complex Terrain Dispersion Model (CTDM)</i>	131
6.4.4.1	DISPERSION PARAMETERS	133
6.4.4.2	CONCENTRATION EQUATION FOR LIFT (FLOW ABOVE H_d)	133
6.4.4.3	CONCENTRATION EQUATION FOR WRAP (FLOW BELOW H_d)	135
6.4.5	<i>Evaluation of CTDM</i>	135

6.5 Mesoscale flow models that include diffusion algorithms	137
6.5.1 <i>General principles</i>	137
6.5.1.1 APPROACH 1—LAGRANGIAN PARTICLE DIFFUSION	138
6.5.1.2 APPROACH 2—USE OF DIFFUSION EQUATION	139
6.5.2 <i>Evaluation of mesoscale grid-based diffusion models in rugged terrain</i>	141
6.6 Summary of findings and recommendations	141
<i>Acknowledgments</i>	142

Chapter 7. Fluid Dynamics of Flow over Hills/Mountains—Insights Obtained through Physical Modeling
—ROBERT N. MERONEY

ABSTRACT	145
7.1 Introduction	145
7.1.1 <i>Advantages and disadvantages of fluid modeling</i>	145
7.1.2 <i>Historical perspectives</i>	146
7.2 Similarity considerations	146
7.2.1 <i>Similitude parameters</i>	147
7.2.2 <i>Partial simulation of complex terrain flows</i>	147
7.2.3 <i>Performance envelopes for fluid modeling</i>	148
7.2.3.1 NEUTRAL AIRFLOW MODELS	149
7.2.3.2 VALLEY DRAINAGE FLOWS	150
7.2.3.3 VERIFICATION EVIDENCE	150
7.3 Facilities for fluid modeling of complex terrain meteorology	150
7.3.1 <i>Wind tunnels</i>	151
7.3.2 <i>Drainage flow facilities</i>	151
7.3.3 <i>Water channels and rotating tanks</i>	151
7.3.4 <i>Instrumentation</i>	152
7.4 Neutral flow over hills, ramps, and escarpments	152
7.4.1 <i>Idealized two-dimensional terrain flow studies</i>	152
7.4.1.1 EFFECTS OF RIDGE SHAPE	153
7.4.1.2 EFFECTS OF TURBULENCE	155
7.4.1.3 EFFECTS OF SURFACE ROUGHNESS	155
7.4.2 <i>Idealized three-dimensional terrain flow studies</i>	156
7.4.3 <i>Field/laboratory comparisons</i>	157
7.4.3.1 RAKAIA RIVER GORGE, NEW ZEALAND	158
7.4.3.2 GEBBIES PASS, BANKS PENINSULA, NEW ZEALAND	158
7.4.3.3 KAHUKU POINT, OAHU, HAWAII	159
7.4.3.4 ASKERVEIN HILL PROJECT, OUTER HEBRIDES, SCOTLAND	159
7.4.4 <i>Conclusions from neutral airflow terrain studies</i>	160
7.5 Stratified flow over hills and ramps	161
7.5.1 <i>Idealized two-dimensional flow domains for waves and blocking</i>	161
7.5.2 <i>Downslope winds, valley flows induced by crosswinds</i>	162
7.5.3 <i>Idealized three-dimensional terrain studies</i>	163
7.5.4 <i>Field/laboratory comparisons</i>	165
7.5.5 <i>Conclusions from stratified airflow terrain studies</i>	166
7.6 Drainage flow phenomena	167
7.7 Diffusion phenomena in complex terrain	168
7.8 Summary	171

CONTENTS

Chapter 8. Remote Sensing of Atmospheric Processes over Complex Terrain

—W. D. NEFF	173
ABSTRACT	173
8.1 Introduction	173
8.2 Remote sensing techniques	174
8.2.1 <i>Scattering mechanisms</i>	174
8.2.2 <i>The role of turbulence microstructure in remote sensing</i>	175
8.2.2.1 STATICALLY UNSTABLE CONDITIONS	176
8.2.2.2 STATICALLY STABLE CONDITIONS	176
8.2.3 <i>Sampling geometries</i>	177
8.2.3.1 FIXED-BEAM SYSTEMS	177
8.2.3.2 SCANNING SYSTEMS	180
8.2.4 <i>Instruments</i>	181
8.2.4.1 SODARS	181
8.2.4.2 RADARS	182
8.2.4.3 AEROSOL-MAPPING LIDARS	183
8.2.4.4 DOPPLER LIDARS	184
8.2.4.5 OPTICAL CROSSWIND SENSORS	185
8.3 Major complex terrain field studies using remote sensors	185
8.3.1 <i>Atmospheric Studies in Complex Terrain (ASCOT) Program</i>	185
8.3.2 <i>EPA Complex Terrain Model Development (CTMD) Program</i>	187
8.3.3 <i>Urban and regional air quality studies</i>	187
8.4 Application of remote and in-situ instrumentation to complex terrain studies—case studies ..	188
8.4.1 <i>Sodar observations of simple drainage flows</i>	188
8.4.2 <i>Sodar observation of complex drainages and their interaction with ambient flows</i>	191
8.4.2.1 THE ROLE OF DIFFERENTIAL ACCELERATION OF AIR MASSES IN ECHO CREATION	191
8.4.2.2 ENTRAINMENT BY THE EXTERNAL WIND—TURBULENCE AND INSTABILITY	193
8.4.3 <i>Remote sensor observation of waves in complex terrain</i>	194
8.4.3.1 LONG-PERIOD OSCILLATIONS OBSERVED IN COMPLEX TERRAIN FLOWS	195
8.4.3.2 SCALE ANALYSIS	196
8.4.3.3 SURFACE WIND ANALYSIS	196
8.4.3.4 WAVES ASSOCIATED WITH FLOW OVER RIDGES AND MOUNTAINS	199
8.4.4 <i>Volume flux in simple drainage flows</i>	200
8.4.5 <i>Main canyon mass fluxes and merging</i>	203
8.4.5.1 LIDAR DATA ANALYSIS AND CORRECTION	203
8.4.5.2 VOLUME FLUX GROWTH AND THE ROLE OF TRIBUTARIES	205
8.4.5.3 THE MERGING OF DRAINAGE FLOWS FROM VALLEYS WITH DIFFERENT PHYSICAL CHARACTERISTICS	205
8.4.5.4 COMPARISON OF LIDAR OBSERVATIONS WITH OTHER MEASUREMENT METHODS IN COMPLEX TERRAIN	208
8.4.6 <i>The role of remote and in-situ sensors in the study of elevated plumes during the 1984 CTMD experiment</i>	209
8.4.6.1 BACKGROUND	209
8.4.6.2 LIDAR AEROSOL PLUME MAPPING	209
8.4.6.3 COMPLEX TERRAIN PROCESSES AFFECTING PLUME TRANSPORT AND DISPERSION	209
8.4.6.4 INTERPRETATION OF ELEVATED PLUMES	211
8.4.7 <i>Interpretation of ground-based plumes during the 1980 ASCOT experiment</i>	212
8.4.8 <i>Remote-sensor observation of day/night transitions in complex terrain</i>	212
8.4.8.1 BACKGROUND	212

8.4.8.2 SODAR OBSERVATIONS OF NOCTURNAL INVERSION DESTRUCTION	213
8.4.8.3 LIDAR OBSERVATIONS OF MORNING FLOW REVERSALS	214
8.4.8.4 THE EVENING TRANSITION TO NOCTURNAL DRAINAGE IN A CONFINED VALLEY	215
8.4.8.5 THE EVENING TRANSITION AND THE EMERGENCE OF DRAINAGE FLOWS ONTO PLAINS	216
8.5 The use of remote sensors in large-scale complex terrain flows	220
8.5.1 <i>Large-scale drainage flows</i>	221
8.5.2 <i>Denver Brown Cloud Study</i>	222
8.5.2.1 DOPPLER LIDAR OBSERVATIONS	223
8.5.2.2 RASS OBSERVATIONS	224
8.6 Summary and future possibilities	226
<i>Acknowledgments</i>	228

Chapter 9. The Role of Mountain Flows in Making Clouds

—ROBERT M. BANTA

—ROBERT M. BANTA	229
ABSTRACT	229
9.1 Introduction	229
9.2 Condensation and stability effects	230
9.2.1 <i>Condensation</i>	230
9.2.2 <i>Lifting profiles</i>	231
9.2.3 <i>Stability effects on cloud forms</i>	233
9.2.4 <i>Interactional effects</i>	234
9.3 Fog, stable clouds, and unstable snow clouds	236
9.3.1 <i>Valley fog</i>	236
9.3.2 <i>Stable rain clouds</i>	236
9.3.2.1 OROGRAPHIC STRATUS	238
9.3.2.1.1 <i>Simple orographic flow</i>	238
9.3.2.1.2 <i>Microphysics</i>	238
9.3.2.1.3 <i>Blocking</i>	240
9.3.2.1.4 <i>Mountain-wave effects</i>	241
9.3.2.1.5 <i>Radiation</i>	241
9.3.2.1.6 <i>Other upslope flows</i>	242
9.3.2.2 INTERACTION WITH LARGER-SCALE PROCESSES	243
9.3.3 <i>Stable snow clouds</i>	244
9.3.3.1 OROGRAPHIC STRATUS	244
9.3.3.2 INTERACTION WITH LARGER-SCALE PROCESSES	247
9.3.4 <i>Unstable snow clouds</i>	248
9.4 Unstable rain clouds	248
9.4.1 <i>Initiation mechanisms</i>	249
9.4.1.1 DIRECT LIFTING TO THE LFC	250
9.4.1.1.1 <i>Potential instability release</i>	250
9.4.1.1.2 <i>Flash flooding</i>	250
9.4.1.2 THERMALLY GENERATED MOUNTAIN CIRCULATIONS	254
9.4.1.2.1 <i>Heat flux and soil moisture effects</i>	256
9.4.1.2.2 <i>Regional differences</i>	256
9.4.1.2.3 <i>Spatial and temporal distribution</i>	257
9.4.1.2.4 <i>Isolated peaks and small ranges</i>	258
9.4.1.2.5 <i>Larger ranges of mountains</i>	262

CONTENTS

9.4.1.2.6 <i>Ambient wind effects on thermally forced mechanisms</i>	263
9.4.1.2.7 <i>Discussion</i>	264
9.4.1.3 OBSTACLE (AERODYNAMIC) EFFECTS	265
9.4.1.3.1 <i>Blocking</i>	266
9.4.1.3.2 <i>Flow deflection</i>	266
9.4.1.3.3 <i>Gravity-wave effects</i>	267
9.4.2 <i>Conditional instability</i>	268
9.4.3 <i>Moisture sources</i>	268
9.4.4 <i>Structures and transitions</i>	269
9.4.4.1 DRY CIRCULATIONS	270
9.4.4.2 CUMULUS AND CUMULUS CONGESTUS	275
9.4.4.3 CUMULONIMBUS	276
9.4.5 <i>Roles for large-scale forcing</i>	277
9.4.6 <i>Discussion</i>	281
9.5 Conclusions	282
Chapter 10. Predictability of Flows over Complex Terrain	
—J. PAEGLE, ROGER A. PIELKE, G. A. DALU, W. MILLER, J. R. GARRATT, T. VUKICEVIC, G. BERRI and M. NICOLINI	285
ABSTRACT	285
10.1 Overview of concepts of chaos and relation to predictability	285
10.2 Predictability studies on the synoptic and global scales	286
10.2.1 <i>Predictability theory for large scales</i>	286
10.2.2 <i>Global experiments</i>	287
10.2.3 <i>Predictability experiments in limited area domains</i>	288
10.3 Predictability studies of turbulence and clouds	289
10.4 Analysis of limited domain predictability	290
10.4.1 <i>Theoretical considerations</i>	290
10.4.2 <i>Predictability of highly forced and dissipated flows</i>	292
10.4.3 <i>Predictability on small scales</i>	294
10.4.4 <i>Spread of lateral boundary errors</i>	295
10.5 Contrast between average and realization parameterization in mesoscale models	297
10.6 Conclusions	298
<i>Acknowledgments</i>	299
References	301

CHAPTER 1

Mountain Meteorology

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ABSTRACT

Some historical footnotes in the field of mountain meteorology are presented. This background provides a brief exposure to the early foundation for current research activities in the collection of meteorological data over complex terrain, physical modeling, and the development of diagnostic and theoretical models of thermal circulations and orographic wave motions. Nascent areas of research, including boundary-layer turbulence and the prediction of weather regimes and pollutant dispersal are assessed in light of the observational and theoretical limitations to be surmounted.

1.1. Introduction

The earth's orography is revealed by almost imperceptible bulges and depressions on a world globe. This is understandable when you consider that the highest mountain barriers only extend the earth's radius by about one-tenth of one percent from its sea-level value. Depressions in the earth's crust are even less noticeable. Nevertheless, the presence of mountains with their endless varieties of passes, valleys, and slopes provides a breeding ground for a myriad of extraordinary meteorological phenomena.

1.2. Some historical footnotes

1.2.1. Surface winds

The history of mountain climate has been etched into the landscape in one form or another. For example, the distortions of trees as shown in Fig. 1.1 are clear indicators of the wind direction over many years. Clues are also obtained from eroded rock surfaces that face the wind. Written history also provides evidence of unusual past events. To Strabo, the Greek historian and geographer, a wind descending through the Rhone Valley onto the Crau Plain was one of the great marvels that ravaged the South of France two thousand years ago. He writes (Jones 1917), "The Black North, a violent and chilly wind, descends upon this plain with exceptional severity; at any rate, it is said that some of the stones are swept and rolled along, and that by the blasts the people are dashed from their vehicles and stripped of both weapons and clothing." This north wind, the mistral, has hardly subsided. It rages frequently through the Rhone Valley and explodes into the Mediterranean basin often at speeds up to 100 mph. Ship logs tell of the havoc inflicted upon vessels caught in the path of the mistral and other winds that have emerged from coastal mountains.

Unusually large wind speeds are common in moun-

tainous terrain and the surrounding foothills, even when the air is not funneled through a narrow gap or valley by the natural barriers on either side. Winds sweeping down the slopes of mountain ranges may match or even exceed the speed of the mistral. Quite often these blasts will cause thermometers to soar, producing temperature increases of 10°C or more in a matter of minutes. This combination of downslope winds and warmth has inspired a long list of names that either describe the phenomenon or its locale. The *oroishi* of Japan is "a wind blowing strong down the slope of a mountain." The *foehn* of the Alps has been traced to the Latin word *favonius*, a warm westerly wind; while the *chinook*, which appears on the eastern slope of the Rockies, is associated with the name of an Indian tribe that lived near the mouth of the Columbia River in the northwestern United States. The "snow eater" is an apt description of the *chinook*, since many inches of snow may be cleared away by this warm, dry wind.

Although in some cases strong downslope winds can cause events ranging from destruction and (*foehn*) sickness to a temporary disruption of daily life, such winds usually represent an intrusion upon the average climatic variability of a locale. The more prevalent gentle breezes, typically less than 10 m s⁻¹, have become embodied in the history of mountain culture. For the most part, these milder winds are of thermal origin. The pressure gradient force that provides the driving mechanism arises from the difference between the temperature of the air above a heated (or cooled) slope and that of the free air at the same level above a nearby valley or level plain. As simple as this widely accepted physical concept appears, the historical development leading to its delineation as the primary controlling mechanism for slope and valley winds has not been without controversy. Vergeiner and Dreiseitl (1987) aptly comment that the nineteenth century disputes over valley wind theory (Hawkes 1947) "seem so picturesque, laborious, and irrelevant today."

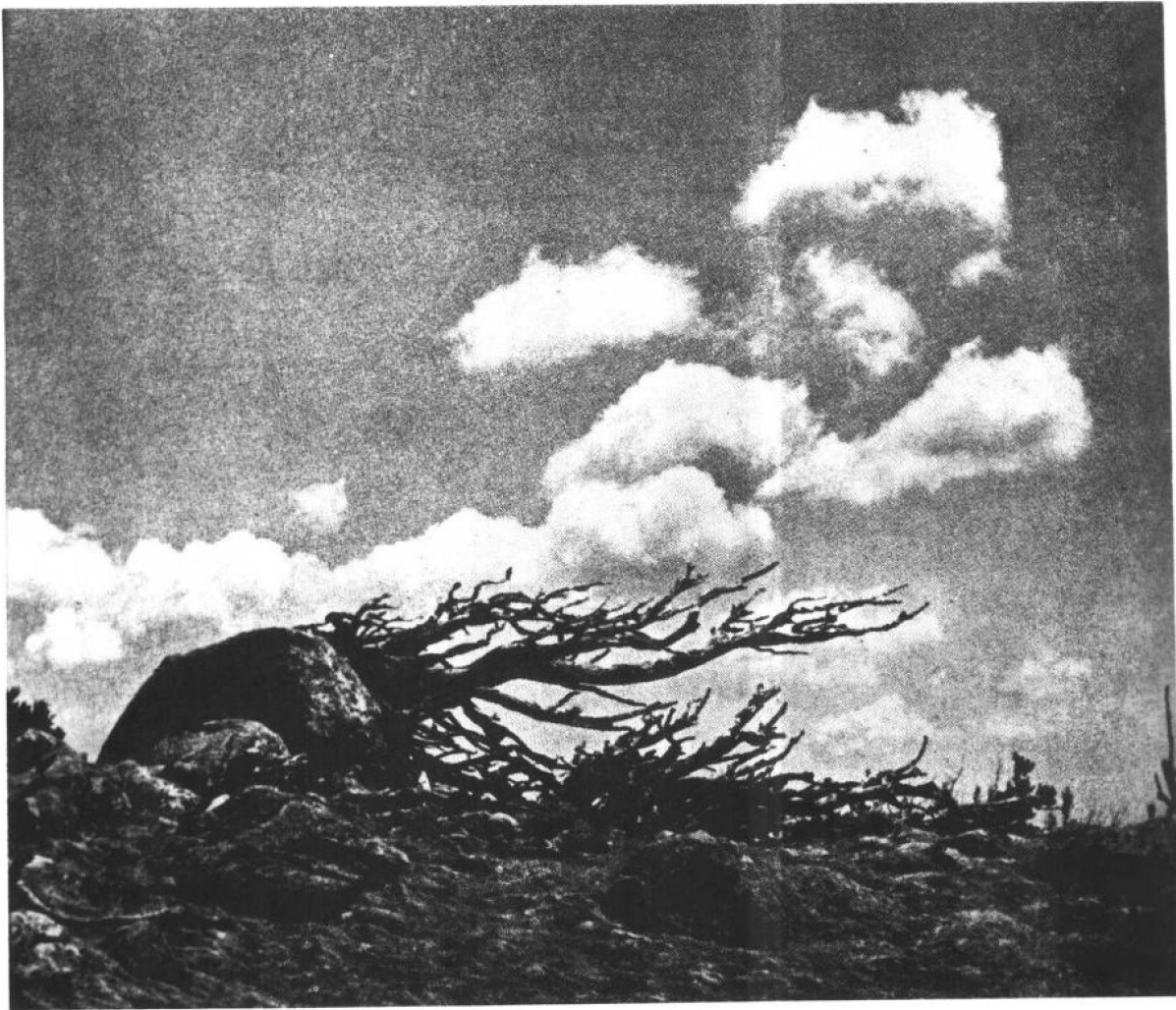


FIG. 1.1. A typical timberline tree at about 11 000 ft on a ridge near Arapahoe Glacier, Colorado (photo by Ives 1964). Coring showed this tree to be about 300 years old.

In contrast to strong winds that sweep out and disperse pollutants, low intensity orographic winds can transport harmful gases and particulate matter *en masse*. Since the weaker wind systems are pervasive over much of the year, the problem of anthropogenic pollution is exacerbated over mountainous terrain. This is not a new problem. For example, damage to crops in the State of Washington during the early 1930s from sulfur fumes from a Canadian smelter became an international controversy (Hewson and Gill 1944). Further, the contribution to smog conditions in the Los Angeles basin and the San Geronio Pass from orographic influences have been under study since at least the 1940s.

1.2.2. Observations and observers

The following accounts have been extracted from the daily journal of meteorological observations made on the summit of Pike's Peak, Colorado, between 1874 and 1888

(Annals of the Astronomical Observatory of Harvard College 1889).

November 30, 1875—Observer shot a large mountain lion this morning.

June 16, 1876—At 5:30 P.M. as the observer was sitting on a rock near the summit, a blinding flash of lightning darted from a cloud seemingly not more than five hundred feet northeast of him, accompanied by a sharp, quick, deafening report, and at the same time he felt the electricity dart through his entire person, jerking his extremities together as though by a most violent convulsion, and leaving lightning sensations in them for a quarter of an hour afterwards.

May 11, 1881—A hurricane struck the summit during the night, wind attaining a maximum velocity of one hundred and twelve miles per hour; at 12:15 A.M. the anemometer cups were blown from their socket and carried away. From this time until 2:30 A.M. the wind in-

creased in violence and the estimated velocity must have been one hundred and fifty miles per hour.

July 1, 1882—At 4:31 P.M., during a heavy fall of hail, a bolt of lightning struck the station building near the southeast corner, having followed the course of the telegraph wire a distance of several rods. The fluid passed through the outer partition walls and entered the office in the southeast corner near the stove, tearing up the floor, melting and tearing off the zinc sheeting around the stove, jumped to the self-register, which it demolished, also the regulator clock on the wall, burned up completely the office wires, and, passing out the north window to the roof, burned out the dial of the anemometer. The explosion was terrific, breaking out every light in the office windows, and, bruising both observers.

The fact that many meteorological observations have been accumulated at Pike's Peak and at other mountain observatories¹ must be attributed to the tenacity of observers, who were exposed to perilous conditions. However, individuals confined to fixed mountain observing sites are not the only ones exposed to the hazards of weather observing. For instance, meteorological observations have been brought back from climbing assaults on Mounts Everest (Longstaff 1923) and Kilimanjaro (Hunt 1947). To the climbers involved in these expeditions, the foremost consideration is climbing the mountain—all other tasks are subordinate. The difficulty of recording observations during such ventures is dramatized in a report of the 1924 Everest expedition (Sommervell 1926). Although daily observations along this route were taken during May and early June, it should be underscored that "the greatest credit is due to those members of the expedition who summoned up the strength to swing a thermometer for five minutes, or to go out in a blizzard to see what was last night's minimum."

Fortunately, heroic deeds are not always a by-product of acquiring meteorological information above mountainous terrain. Besides outfitting climbers with instruments, a cog railroad at Mount Washington, New Hampshire, and a cable car reaching the Zugspitze Peak in Germany have been used as platforms for meteorological measurements; however, the accumulation of data through the efforts of climbing expeditions and by the use of moving surface vehicles have been sporadic endeavors. The quest for information near the surface of the earth is, for the most part, aided by routine measurements made on a day-to-day basis at ground level meteorological stations situated in virtually all land areas of the globe.

¹ Stone (1934) presents a succinct, highly informative summary of the history of meteorological observations obtained at North American and Pacific island mountain observatories.

1.2.3. *The discovery of atmospheric waves*

The realization that gliders or sailplanes could be used as atmospheric probes developed during the decade following the late 1920s, when the art of soaring was enjoying wide popularity in Europe. Evidence of pronounced vertical undulations of the airflow in the lee of mountain ridges and isolated peaks began to emerge when pilots were able to exploit these currents to rise to great heights and stay aloft for long periods of time. In fact, altitude records were frequently being surpassed during these years.

As Queney et al. (1960) point out, "Theoretical workers had not been idle," as a body of descriptive information about the characteristics of these undulations was being established. It is further noted that Queney, in his paper "Influence du Relief sur les Éléments Météorologiques," did in fact provide the theoretical explanation of the so-called mountain lee wave in 1936 *before* this phenomenon was properly depicted by observational means. Since Queney's pioneering work the study of lee waves has flourished. Not only has the theory been honed, for example, by Scorer (1949) and Long (1953b) among others, but field programs to investigate lee-wave characteristics have been carried out over many of the prominent peaks and ridges that characterize the earth's orography. The comprehensive monograph by Queney et al. and the extended reviews by Nicholls (1973) and Smith (1979) provide evidence of the worldwide scope of these studies.

It is now well established that lee waves are simply internal gravity waves maintained in an essentially steady state in a stably stratified airstream. It is also evident that, similar to surface water waves, lee waves may overturn and be associated with extremely turbulent conditions. Striking evidence for highly unusual and hazardous conditions was uncovered during the comprehensive field investigation of airflow over the Sierra Nevada range in the vicinity of Bishop, California (Holmboe and Klieforth 1957). Both gliders and powered aircraft were used during the 1951–52 and 1955 field programs to gather meteorological data. Vertical currents exceeding 10 m s^{-1} were encountered within the fully developed "Bishop wave." However, in one reported incident, the mountain induced updrafts in this locale were found to be of such intensity that the pilot of a P-38 aircraft was able to feather the propellers and soar like a glider for over an hour on the cushion of rising air. These updrafts were estimated to be about 40 m s^{-1} !

1.3. Current directions

Orographic flows encompass all scales of motion, and disturbances forced by orography may even extend to thermospheric altitudes. Both observational analyses and numerical model experiments have revealed that the planetary general circulation including the energy, mo-

mentum, heat, and moisture balances is significantly affected by orography. There continues to be widespread interest in the scientific exploration of phenomena either produced or affected by local inhomogeneities of the earth's terrain. The contributors to this volume consider those orographic responses that are principally confined to the troposphere and are of sufficiently small horizontal scale ($L < 10^5$ m) that they may be completely unobserved by the present synoptic-scale observational network.

The two most important mechanisms that force orographic flows are thermal and mechanical in nature. *Thermal circulations* are intimately related to differential heating and cooling associated with diurnal insolation. *Wave motions* arise because a resting state of stable stratification is perturbed by the low-level undulations of an incident airstream that is constrained to follow the topographic surface profile. The interactions between thermal and mechanical forcing give rise to convective and stratiform clouds, and to both stably stratified turbulence and small-scale instability that characterize the orographic boundary-layer regime. This wide range of physical phenomena are not necessarily restricted to orographic flows. Yet the fact that excitation, maintenance, and dissipation of these flows are intimately related to complex terrain features does not mitigate the problems of data collection, analysis, and prediction.

In situ measurements by ground-based measuring systems and by balloons and aircraft have traditionally been the mainstays of field programs. These traditional methods of acquiring data will undoubtedly continue for the foreseeable future, but will be increasingly supplemented by physical model experiments on the laboratory scale, and

by remote sensing of thermal and motion fields and cloud features that characterize the real atmosphere. Expansion of these facilities will continue to depend on technological advances that are difficult to predict. Among the more promising observational tools is Doppler lidar, which provides real-time two-dimensional wind vectors over 10 s of kilometers with a resolution of about one-third of a kilometer (e.g., Bilbro et al. 1984). This range and resolution provides data for relatively detailed analyses of orographic waves and convective motions, and its usefulness for depicting fields adjacent to complex terrain has recently been demonstrated by Post and Neff (1986).

There has been notable progress, in recent years, both in the analysis and the modeling of thermal circulations, drainage flows, mountain waves, and related downslope windstorms. Yet the problems of data paucity and the sensitivity of physical responses to terrain features continue to pose formidable barriers to comparable progress in nascent research directed toward basic turbulent processes, and to the development of models for the reliable prediction of weather regimes and transport of pollutants over complex terrain.

The authors of the following chapters have provided historical perspectives and assessments of current knowledge that are intended to provide the fulcrum for the development of research goals in the decades ahead.

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CHAPTER 2

Observations of Thermally Developed Wind Systems in Mountainous Terrain

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ABSTRACT

Slope and valley wind systems are local thermally driven circulations that form frequently in complex terrain areas. Recent research has focused on the temperature structure along the slope and valley axes that leads to the wind systems. Two new tools being used in these analyses include the topographic amplification factor, which quantifies the role of the topography in producing bulk temperature gradients along a valley's axis, and atmospheric heat budgets, which identify key physical processes leading to changes in temperature structure. Both tools are in an early stage of development, are being applied primarily to steady-state nighttime periods, and are leading to new concepts and understanding.

Recent climatological evidence in Austria's Inn Valley and in several Colorado valleys supports the concept that valley winds are driven by horizontal pressure gradients that are built up hydrostatically by the changing temperature structure along a valley's length. Topographic amplification factors appear to be useful in assessing the strength of valley wind systems. Several components of valley atmospheric heat budgets have proven difficult to measure, and large imbalances are being experienced. Several recent experiments, in a range of climatological regimes, suggest that measured nighttime surface sensible heat fluxes are too small to result in balances. This may be caused by measurement errors or by nonrepresentative measurements. The advective and radiative flux divergence components are also uncertain.

A simple conceptual model of diurnal wind and temperature structure evolution in deep valleys is presented. During the morning transition period, upslope flows form over heated valley sidewalls and compensatory subsidence over the valley center produces warming that eventually reverses the down-valley winds. The key role of vertical motions in transferring energy through the valley atmosphere during the morning transition period has been demonstrated by field and modeling studies.

The evening transition period has received little observational attention, and the key physical processes are not yet well known. Investigation of slope wind systems has focused mostly on the nighttime flows. Flows on the sides of isolated mountains are reasonably well understood when external flows are weak, but slope flows on valley sidewalls are complicated by the continued evolution of temperature structure within the valley and the strong influence of the overlying along-valley flows.

Recent experiments have shown that thermally driven flows within the topography may be influenced in subtle ways by the overlying circulations. This influence is nearly always present to some extent, but has not yet been systematically investigated. Recent research on strong winds that issue from a valley's exit at night and on tributary flows is briefly summarized, and some comments are made on Maloja winds and antiwind systems. The chapter ends with a summary of topics needing further research.

2.1. Introduction to diurnal mountain winds

Two classifications of diurnal mountain wind systems are generally recognized (Fig. 2.1). *Slope winds* blow parallel to the inclination of the sidewalls and are called upslope and downslope winds. The slope winds are produced by buoyancy forces induced by temperature differences between the air adjacent to the slope and the ambient air outside the slope boundary layer. Typically, slope winds blow up the slope by day and down the slope by night. *Valley winds* blow parallel to the longitudinal axis of a valley. These winds are produced by horizontal pressure gradients that develop as a result of temperature differences that form along the valley axis or temperature differences between the air in the valley and the air at the same height over the adjacent plain. Valley winds typically blow up-valley during daytime and down-valley during nighttime, although their onset can be substantially de-

layed in valleys where large atmospheric volumes are involved. A variety of names have been applied to these wind systems, with usage varying somewhat from country to country. Alternative terminology for the diurnal mountain winds is listed in Table 2.1.

Study of the pure thermally developed winds is complicated by the influence of other wind systems that develop on different scales, of regional pressure gradients superimposed on the topography, and of mechanical effects induced by the topography on the wind systems themselves or on overlying wind systems. In this chapter, we emphasize thermally developed wind systems, and these complications will be considered as modifying influences.

Increases in understanding of slope and valley wind systems in the last decade have come from the combined efforts of observationalists, theoreticians, and modelers. This chapter deals primarily with observations of ther-