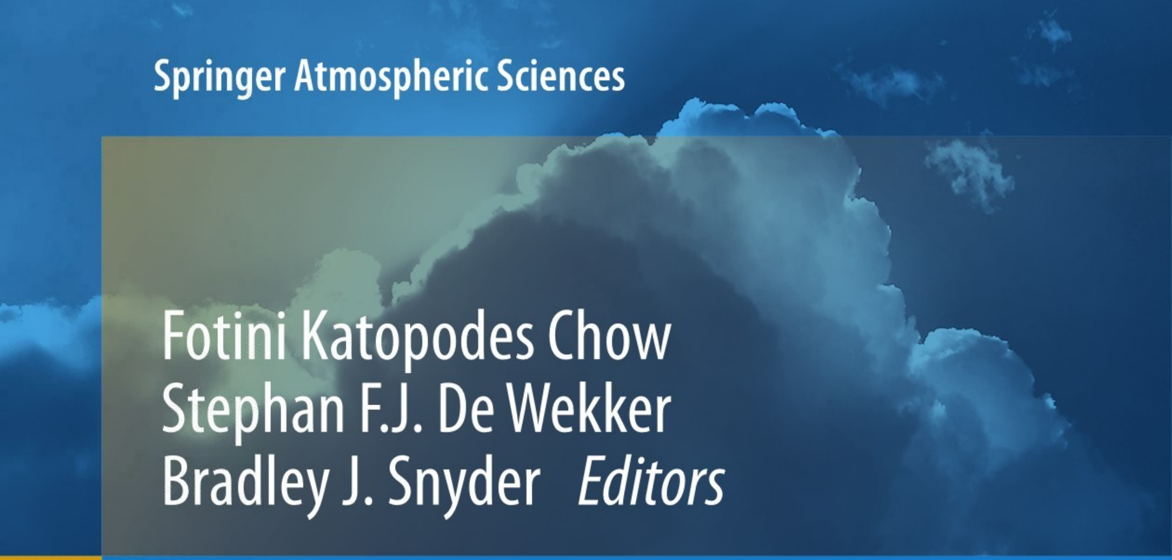

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Fotini Katopodes Chow
Stephan F.J. De Wekker
Bradley J. Snyder *Editors*

Mountain Weather Research and Forecasting

Recent Progress and Current Challenges

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Preface

This book is the result of a multiyear effort that began with the organization of a workshop designed to bring researchers and forecasters together to discuss current progress and challenges in mountain weather. The chapters herein represent the topics from this Mountain Weather Workshop, which took place in Whistler, British Columbia, Canada, 5–8 August 2008. The inspiration for the workshop and book arose under the guidance of the American Meteorological Society (AMS) Mountain Meteorology Committee.

One of the main goals of the workshop was to bridge the gap between the research and forecasting communities by providing a forum for extended discussion and joint education. The workshop consisted of lectures given by 13 distinguished speakers, several discussion opportunities in small groups, and a day of laboratory exercises designed for forecaster training for the 2010 Winter Olympics in Vancouver. The lectures provided a detailed overview of important and emerging topics in mountain meteorology. About 100 participants attended, roughly evenly split among forecasters, researchers, and graduate students (see Fig. 12.2 for a picture of participants). One of the highlights of the week was a group activity to design the best observation and modeling system to nowcast for the Olympic ski jump event; this was an excellent opportunity for researchers and operational forecasters to work together and "bridge the gap." The lectures from the workshop can be accessed online in the COMET MetEd tutorial collection (http://www.meted.ucar.edu/training_module.php?id=878).

The chapters in this book have been written with the intent to provide a thorough overview of each topic with an emphasis on recent research and progress in the field, especially since the last collection of topics in mountain meteorology was published more than two decades ago (Blumen 1990). It is our hope that this new offering will be used extensively in mountain weather courses at universities and forecast offices and also used as a general reference book for researchers, forecasters, and students. Readers will be provided with a broad understanding of the fundamental principles driving flow over complex terrain, including historical context for recent developments and future directions for researchers and forecasters. For academic

Fig. P1.1 View of the PEAK 2 PEAK gondola connecting Whistler and Blackcomb mountains, looking across toward Blackcomb. Whistler village is on the far left (© James Dunning. Reprinted with permission)

researchers, the book will provide some insight into issues important to the forecasting community. For the forecasting community, we hope the book will provide training on fundamentals of flows specific to mountainous regions which are notoriously difficult to predict, understanding of current research challenges, and an opportunity to learn about the latest contributions and advancements to the field. Our goal of bridging the gap between research and forecasting with this book is aptly captured in the image below showing Whistler and Blackcomb mountains, connected by the new PEAK 2 PEAK gondola, built for the 2010 Winter Olympics, bridging the gap between the two mountains (Fig. P1.1).

The first chapter provides an overview of mountain weather and forecasting challenges specific to complex terrain. This is followed by chapters that focus on diurnal mountain/valley flows that develop under calm conditions (Chap. 2) and dynamically driven winds under strong forcing (Chap. 3). The focus then shifts to other specific phenomena that are difficult to understand and predict in mountain regions: Alpine foehn (Chap. 4) and boundary layer phenomena and air quality (Chap. 5). The following two chapters address processes that bring wet mountain weather, in the form of rain, snow, or other hydrometeors, with a discussion of specific orographic precipitation processes (Chap. 6) and the details of microphysics parameterizations (Chap. 7). Having covered the major physical processes, the book shifts to observation and modeling techniques used in mountain regions. First, a detailed discussion of field measurements in complex terrain is given (Chap. 8).

Then, the following three chapters describe the basics of mesoscale numerical modeling (Chap. 9), model configuration and physical parameterizations such as turbulence (Chap. 10), and model applications in operational forecasting (Chap. 11). The book concludes with a chapter that discusses the current state of research and forecasting in complex terrain, including a vision of how to bridge the gap in the future (Chap. 12).

We are quite fortunate to have a set of conscientious and thorough authors who have contributed their knowledge and expertise to create this book, largely in their spare time. We are also extremely grateful to the many reviewers who were involved in ensuring the quality of this book. Given the length of some of the chapters, we were particularly impressed by the care they took to thoroughly review the chapter content, from comments on overall structure to details on style and formatting.

Funding to support the publication of this book and for student travel to the workshop was provided by the National Science Foundation (NSF) (award ATM-0810090). Funding for the workshop was provided by the American Meteorological Society (AMS), the University Corporation for Atmospheric Research (UCAR) acting on behalf of the Cooperative Program for Operational Meteorology, Education and Training (COMET), and the Meteorological Service of Canada (MSC). The workshop was mainly organized by us (editors of this book) with the help of many others on the AMS Mountain Meteorology Committee, in addition to Cara Campbell at AMS. We thank our colleagues who were AMS Mountain Meteorology Committee members with us over the years (Brian Colle, Lisa Darby, Mike Meyers, Stephen Mobbs, Greg Poulos, Heather Reeves, Alex Reinecke, Simon Vosper, Doug Wesley, and David Whiteman) and members of the AMS publications department (Peter Lamb, Sarah Jane Shangraw, and Ken Heideman) for their support of this effort.

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Chapter 1
Mountain Weather Prediction: Phenomenological Challenges and Forecast Methodology

Michael P. Meyers and W. James Steenburgh

Abstract This chapter summarizes the modern practice of weather analysis and forecasting in complex terrain with special emphasis placed on the role of humans. Weather in areas of complex terrain affects roughly half of the world's land surface, population, and surface runoff, and frequently poses a threat to lives and property. Mountain weather phenomena also impact a diverse group of users, which may have both beneficial and detrimental implications on societal and economic levels.

Advances in forecast skill derive not only from advances in numerical weather prediction, geophysical observations, and cyber infrastructure, but also improvements in the utilization of these advances by operational weather forecasters. Precipitation skill scores during the past two decades, for example, show that operational weather forecasters have maintained a consistent threat score advantage over numerical precipitation forecasts. Although the role of human forecasters is evolving, for many applications, the so-called "human-machine mix" continues to provide an improved product over what can be produced by automated systems alone. To produce the best forecasts possible for the benefit of society, it is crucial for the mountain meteorologist to possess an in-depth knowledge of mountain weather phenomena and the tools and techniques used for atmospheric observations and prediction in complex terrain.

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1.1 Introduction

Contemporary mountain weather forecasting involves the integration of geophysical observations, numerical and statistical analysis and modeling, and human cognition to meet the challenges posed by a diverse range of terrain-induced phenomena. This integration, known as the "human-machine mix" (Snellman 1977), produces significantly better forecasts than can be produced by automated systems alone, with the value added by human cognition representing a 5–10 year advance in numerical weather prediction skill (Bosart 2003; Steenburgh et al. 2012, Chap. 12). The human-machine mix is only effective, however, when operational meteorologists possess in-depth knowledge of mountain weather phenomena and the tools and techniques used for atmospheric observation and prediction in complex terrain.

In this chapter we provide a review of the major phenomenological challenges confronting mountain meteorologists and *qualitatively* describe the contemporary forecast process, with emphasis on the human element over complex terrain. Our goal is to provide a foundation for subsequent chapters that focus on specific mountain weather phenomena or forecast tools and techniques, including numerical weather prediction, which ultimately must be integrated to produce societally relevant forecasts. We conclude with a discussion of ongoing forecast applications in areas of complex terrain.

1.2 Phenomenological Challenges in Complex Terrain

Mountains cover 25% of the Earth's land surface, contain 26% of the global population, and produce 32% of the surface runoff (Meybeck et al. 2001). Hills and plateaus account for another 21% of the land surface, 20% of the population, and 19% of the runoff. Thus, the weather in areas of complex terrain affects roughly half of the world's land surface, population, and surface runoff. The numbers are greater if one considers the remote effects of mountains on the general circulation, storm tracks, moisture transport, and river runoff.

The protection of lives and property from high impact events is a forecast priority; in addition, accurate forecasts of day-to-day mountain weather variability benefit commerce and the general public. For instance, many mountain recreationalists are impacted by mountain weather. In the United States, the total number of people who participated in outdoor activities in 2007 is estimated at 217 million (Cordell 2008). Outdoor recreation (camping, snow sports, rafting, hiking, hunting and fishing, etc.) contributes $730 billion to the economy annually and supports 6.5 million jobs (1 in 20 U.S. jobs) according to the Outdoor Industry Association (http://www.outdoorindustry.org). In addition to the general population, numerous other industries are dependent on weather that occurs over complex terrain.

The primary phenomenological challenges confronting mountain meteorologists include: (a) snow and (b) ice storms produced by orographic precipitation and/or terrain-induced cold advection and cold-air damming; (c) floods, landslides, and debris flows generated by orographic rainfall and/or terrain-induced deep convection; (d) droughts; (e) extreme wildfire spread and behavior driven by fuels, topography, and weather; (f) severe local windstorms created by high-amplitude mountain waves and gap flows; (g) severe convective storms; and (h) cold-air pools and associated air quality hazards. In addition to loss of life, high-impact weather events generated by these phenomena can produce staggering economic losses, often requiring participation from government entities to address them. To adequately meet these phenomenological challenges, forecasters need not only a strong foundation in mountain meteorology (also see: Whiteman 2000), but also knowledge in areas such as climatology, hydrology, ecology, land-surface processes, and societal vulnerability.

1.2.1 Snowstorms

Snowstorms (also see Chaps. 6 and 7) exert a heavy toll on public safety and transportation. The average annual cost of snow removal for public roadways in the United States exceeds US $2 billion (Doesken and Judson 1997; National Research Council (NRC) 2004). Thornes (2000) estimated that the United Kingdom spends over US $2 billion annually on direct and indirect costs related to winter maintenance of roadways and road traffic delays. Airport delays and closures cost US $3 billion annually for US carriers and produce adverse sociological impacts for the travelers. The potential benefits from improved forecasting of snow and icing diagnostics at U.S. airports exceed US $600 million annually (Adams et al. 2004).

In mountainous regions, the economic losses due to snow-related highway closures are considerable (Fig. 1.1). For example, in Europe, during a prolonged snowy period in February 1999, more than 40 tourist resorts in the Swiss Alps were cut off from the outside world due to road closures for up to 14 consecutive days, resulting in indirect costs of ∼US $200 million (Nöthiger and Elsasser 2004). In the United States, losses produced by the snow-related closure of Interstate 90, the major highway bisecting the Cascade Mountains of Washington State, are estimated at US $700,000 per hour, and similar shut downs of Interstates 70 and 80 through Colorado and Wyoming, respectively, approach US $1 million per hour. Poor driving conditions due to weather cause over 1.5 million vehicular accidents in the United States annually with total economic costs of US $42 billion dollars. These vehicular accidents result in 800,000 injuries with 7,400 fatalities indirectly related to poor weather conditions (National Research Council 2004). A conservative estimate of the annual costs of weather-related vehicular accidents in Canada is US $1.1 billion dollars (Andrey et al. 2001).

Snowstorms seriously impact urban corridors adjacent to mountain locations. Personal claims from the March 2003 Colorado Front Range Blizzard exceeded US $93 million. However, with the bad comes the good: during the blizzard the

Fig. 1.1 Snow removal in the southwestern Colorado Mountains (Courtesy of the Colorado Avalanche Information Center [CAIC] and the Colorado Department of Transportation [CDOT])

snowpack in the Colorado Rockies went from inadequate to above 100% of average. A senior agriculturist for the Western Sugar Cooperative in eastern Colorado called it a billion-dollar storm due to its positive impact on the snowpack (Kohler 2003).

Avalanches are another potential impact of winter storms in complex terrain (Fig. 1.2). Recent major weather related avalanche disasters have killed 14 in Súðavík, Iceland in January 1995; 20 in Flateyri, Iceland in October 1995 (Jóhannesson and Arnalds 2001); and 55 in Swiss and Austrian villages in February 1999 (Keiler et al. 2005). Avalanche disasters are not restricted to mountainous regions. On New Year's Day 1999, nine were killed in Kangiqsualujjuaq, Quebec when an avalanche ran down a steep hill and hit the local school (Branswell 1999).

Conversely, mountain snowstorms can be a winter recreationalist's dream (Fig. 1.3) and provide benefits for the winter recreational economy. There are approximately 6,000 ski resorts with nearly 400 million skier days per year (i.e., 1 day of downhill skiing or snowboarding with a pass/ticket) globally (Hudson 2002; Skistar 2009). Europe is the largest market with ~200 million skier days per year, followed by North America with 80 million skier days per year (http://www.nsaa.org/nsaa/press). The ski industry in the United States has annual revenue of approximately US $12 billion (Scott 2006). Additionally, in North America, snowmobilers spend more than US $28 billion annually on equipment, clothing,

Fig. 1.2 Avalanche over the southwestern Colorado Mountains (Courtesy of CAIC and CDOT)

accessories and vacations (US $6 billion in Canada) (International Snowmobile Manufacturers Association http://www.snowmobile.org). Avalanches can, however, pose a hazard for these recreationists. From 1991 to 2001, the International Commission of Avalanche Rescue (http://www.ikar-cisa.org) reports nearly 1,500 fatalities due to avalanches with France and the United States having the two highest percentages of deaths.

1.2.2 Ice-Storms

The advection and/or entrenchment of cold air by cold-air damming (Forbes et al. 1987; Bell and Bosart 1988) and orographic channeling affect the locations of rain-snow transition zones in winter storms (also see: Chaps. 6 and 7). The January 1998 ice storm that devastated the northeastern United States and southeastern Canada

Fig. 1.3 Recreational skiing in Colorado (Courtesy of Meyers)

produced 80–100 mm of freezing rain over a 5 day period, causing more than US $4 billion in economic damage, including US $3 billion in Canada (Reagan 1998; Roebber and Gyakum 2003). Cold-air channeling within the St. Lawrence, Ottawa River, and Lake Champlain valleys enabled the persistence of low-level cold air within the precipitating region, controlled the position of the surface-based freezing line, and enhanced precipitation rates through frontogenesis. Such orographic channeling can also lower freezing levels and snow levels in interior basins and mountain passes, such as the Columbia River Basin, Snake River Plain, Columbia River Gorge, Snoqualmie Pass, and the Frazier River Valley in the Cascade Mountains and Coast Range of western North America (e.g., Decker 1979; Ferber et al. 1993; Steenburgh et al. 1997).

1.2.3 Floods, Flash Floods and Debris Flows

Floods are among the most common of geologic hazards worldwide. Typically, most river systems flood (i.e., leave their confining channels and flow outward onto the adjacent floodplain) every year or two. There are two types of floods: regional floods that can last for several weeks or months, and flash floods that last for minutes to hours. Both are dangerous and capable of adversely impacting lives and property (National Research Council 2005; http://www.azgs.state.az.us/).

Flooding produced by orographic precipitation is responsible for many of the weather-related natural disasters in mountainous regions. Of the 13 weather-related disasters observed in the western United States since 1980 with damages and costs exceeding US $1 billion, four were produced by heavy and/or persistent orographic precipitation and associated surface snowmelt (Lott and Ross 2006). In the United States, floods cost upwards of US $6 billion and about 140 people are killed by floods each year (Knutson 2001). In Europe, losses from the Italian Piedmont floods of 1994 included 64 casualties and US $9 billion in property damage (Linnerooth-Bayer and Amendola 2003; Barredo 2007). The damage and fatalities produced by these events frequently extend over the flood plains well removed from the orography responsible for the precipitation enhancement.

Orography also contributes to localized but extremely hazardous flash floods by influencing the formation and movement of deep convection and mesoscale convective systems. Well documented examples include the Rapid City Flash Flood of June 1972, which killed 238 and produced US $100 million in property damage in South Dakota; the Big Thompson Canyon Flood of July 1976, which killed 145 and produced US $25.5 million in property damage in Colorado; the Vaison-La-Romaine Flash Flood of September 1992, which killed 46 and produced US $460 million in property damage in southeastern France (Maddox et al. 1978; Sénési et al. 1996; Barredo 2007); and the September 2002 severe flood event in the western Mediterranean mountainous region of southern France (Nuissier et al. 2008; Ducrocq et al. 2008) which killed 24 people and produced an economic damage estimated at nearly US $2 billion (Huet et al. 2003).

Debris flows can occur on steep slopes where loose, unconsolidated earthen materials, such as soils and rocks, experience gravitational acceleration during heavy rains, glacial melt or snowmelt (Iverson 1997). Debris flows can move downslope rapidly, at speeds of greater than 10 $\mathrm{m\ s^{-1}}$; their less viscous, fine-grained relative, mudflows, have been clocked traveling at 40 $\mathrm{m\ s^{-1}}$ in steep mountain canyons. Wildfires may potentially increase the risks for debris flow development by destroying vegetation and making soils more hydrophobic (Cannon et al. 1998, 2001, 2003; Cannon and Reneau 2000). The major hazards of debris flows are from the impact of earthen materials, such as boulders and rocks, and being buried or carried away by the flow. Debris flows can be devastating to life and property. In the United States, damage estimates due to debris flows are close to US $3 billion annually (Restrepo et al. 2008). During December of 1999 exceptionally heavy rain triggered catastrophic floods and landslides along portions of the mountainous coastal region of northern Venezuela (Lyon 2003). Over 10,000 fatalities were reported and the cost of reconstruction was estimated at nearly US $2 billion.

1.2.4 Droughts

One long duration weather phenomenon which may impact short term decision making for a mountain meteorologist, including hydrologists and fire weather meteorologists, is drought. Droughts come in various forms, which may impact society with varying intensities and durations. By definition, a drought is "a period of abnormally dry weather sufficiently prolonged for the lack of water to cause serious hydrologic imbalance (i.e. crop damage, water-supply shortage, etc.) in the affected area" (American Meteorological Society 1986). On an annual basis, average losses and costs in the United States due to drought are estimated to exceed US $8 billion (Knutson 2001).

The main water source for over 30 million people in the mainly arid climate of the southwestern United States is the Colorado River. Snowmelt from mountain snowpack provides over 70% of the water supply for this region (Chang et al. 1987; Christensen et al. 2004), and the estimated benefit of water storage exceeds US $350 billion dollars annually (Adams et al. 2004). Water is also the driving force behind the agricultural industry of the southwestern United States. In California, the agriculture industry accounts for nearly US $150 billion annually according to the California Department of Food and Agriculture (http://www.cdfa.ca.gov/). The economic impacts on the agricultural community due to droughts can be tremendous. The University of California, Davis, estimated that US $2.8 billion in agriculture-related wages, and as many as 95,000 jobs across the valley were potentially lost due to the 2008 drought (Howitt et al. 2009).

Droughts can adversely impact the winter recreational industry, such as skiing and snowmobiling, which depends on mountain snowpack. For example, many skiers and snowboarders tend to favor lower-density, abundant snow (Steenburgh and Alcott 2008), and low quality or meager snow can affect the demand for ski days (Englin and Moeltner 2004). Summertime recreational use is not immune from low snowpack. Low runoff during drought years can significantly reduce white-water rafting revenue, which in Colorado alone, attracts 540,000 visitors and generates US $150 million annually. Recreational fishing and hunting may also be affected by drought. The impact on fish and other aquatic life due to drought may be significant (Matthews and Marsh-Matthews 2003). Drought-depleted ecosystems and wetlands would have a drastic effect on other wildlife.

Drought is not as visually obvious as other weather phenomena in the mountains, but it is perhaps the most devastating to the ecological state because it can significantly weaken a forest's defenses against insect infestation and wildfires (Morris and Walls 2009). Recently, various populations of bark beetles are impacting the western United States and western Canada with unprecedented levels of tree mortality (Fettig et al. 2007). For instance, beetles have devastated several million acres of trees in Colorado and Wyoming by the end of 2008 (Robbins 2008). Extreme drought conditions in mountainous regions may also lead to increased wildfire activity, as was the case in 1988 (Yellowstone National Park Fire) and in 2002 (Hayman, Missionary Ridge and Coal Seam fires in Colorado).

Fig. 1.4 2002 Big Fish Wildfire in Colorado (Photo by Mike Chamberlain; courtesy of the NOAA/NWS/GJT)

1.2.5 Wildfire Behavior

Prescribed and unplanned wildfires (Fig. 1.4) impact tens of millions of acres annually around the world (also see Chap. 2). In the western United States, where the wealth and development of communities has migrated to the wildlands or the wildland-urban interface over the past few decades, there have been eight wildfires since 1980 that have produced more than US $1 billion in damage (Lott and Ross 2006). Of particular safety concern for firefighters are the conditions that lead to fire "blowups", which cause rapid fire spread. Wildfires over complex terrain are especially susceptible to these blowups, due the diurnal changes of surface wind direction and speed, as well as the surface mixing of synoptic and convectively-driven winds.

One of the most devastating wildfires, the Big Burn of 1910, killed at least 78 firefighters and burned millions of acres in northern Idaho and western Montana (National Wildfire Coordination Group 1997). This wildfire raised political awareness of the economic and human impacts produced by wildfires. More recently, from 1990 to 2006, there were 310 fatalities during western US wildland fire operations, including the 1994 Storm King wildfire (14 fatalities) (National Wildfire Coordination Group 2007). The number one cause of death during this time period was burnovers (∼40%), “a situation where personnel or equipment is caught in an advancing flamefront” (National Wildfire Coordination Group 2007), and secondly due to aircraft and vehicular accidents (∼30%). Wildfires often have an adverse impact on recreation and tourism. After the devastating wildfires in Yellowstone National Park in 1988, visits to the park dropped 15% the following year (National Park Service 2009). High wildfire danger may result in the closure of wildland areas, which negatively impact recreation and logging.

1.2.6 Severe Windstorms Created by High-Amplitude Mountain Waves and Gap Flows

Terrain-forced flows such as downslope windstorms and gap winds can produce severe winds, many of which have exotic names like the Chinook along the eastern slopes of the Rocky Mountains, the Mistral of southeast France, the Bora of Slovenia, Croatia, and Bosnia, the Zonda along the east slopes of the Andes in South America, the Taku in Alaska and the Föehn of central Europe (also see: Chaps. 3 and 4). Surface winds during extreme downslope windstorms can exceed hurricane force (>33 m s^{-1}) and associated turbulence, rotors, and aircraft icing present a threat to aviation safety (Nance and Colman 2000). Downslope windstorms are also associated with the rapid spread of wildfires (e.g. Santa Ana [southwest United States], Föehn, Chinook), making some regions which experience these winds particularly prone to extreme fire weather behavior. Terrain-forced flows are also a concern for maritime travel and commerce in and near mountainous coastal zones around the world. It even has been suggested that these downslope windstorms are often associated with illnesses ranging from migraines to psychosis (Soyka 1983).

Less frequent downslope windstorms sometimes occur in a synoptically uncommon flow pattern and represent a difficult forecast problem given their low frequency. In October 1997, while a blizzard was occurring over the Front Range of Colorado (Poulos et al. 2002), an easterly downslope windstorm was occurring over the Mt. Zirkel Wilderness in the north central Colorado Rockies (Meyers et al. 2003). This easterly downslope wind event had devastating ecological consequences, resulting in 13,000 acres of forest blowdown in the Routt National Forest.

Although orography also produces thermally driven winds, they are not typically severe. Exceptions include large-scale katabatic flows such as those that occur along the coast of Antarctica, which can become violent, particularly if they are accelerated through interactions with local topography or enhanced by the large-scale pressure gradient (e.g., Parish and Bromwich 1998).

1.2.7 Severe Convective Storms

Mountainous terrain can have an indirect impact on tornado development by modifying airmasses downstream over the plains. One scenario occurs when the mountains modify the plains environment by providing an elevated mixed layer which results in a higher severe weather potential for tornado development (Lanicci and Warner 1991). Over the mountains, tornadoes are more infrequent than their plains counterparts, but can be significant when they do form. Tornadoes and funnel clouds occur occasionally over the Rocky Mountains during the late spring and summer (Bluestein and Golden 1993). These tornadoes usually develop in non-supercell storms because the vertical shear is usually too weak for supercell formation. Similar type storms have been observed in Switzerland (Linder and Schmid 1996). However, mountain tornadoes can potentially be devastating. Fujita (1989) documented an F4 tornado that crossed the Continental Divide within Yellowstone National Park in Wyoming in 1987. This tornado traveled 24 miles and leveled 15,000 acres of mature pine forest. On 11 August 1999 an F2 tornado developed southwest of downtown Salt Lake City, Utah, and moved directly through the city. This tornado resulted in one fatality, more than 100 injuries and US $170 million in damages (Dunn and Vasiloff 2001). Bosart et al. (2006) analyzed a long-lived supercell that became tornadic over complex terrain in Massachusetts, on 29 May 1995. The F3 tornado left a 50–1,000-m-wide damage path that stretched for ~50 km. Other documented supercell tornadoes over complex terrain include those over the hilly terrain of the upper Rhine Valley of Germany (Hannesen et al. 2000) and over the Colorado Mountains (Bluestein 2000).

Another potentially devastating severe wind that occurs in proximity to mountain locations is the downburst wind or the smaller scale microburst (<4 km). Downburst winds in arid mountain areas like the western United States are frequently dry and develop in an environment with a deep, nearly dry-adiabatic subcloud layer; a shallow moist mid-layer near 500 mb; weak synoptic-scale forcing with only moderate (<25 m s^{-1}) winds aloft; and weak instability [lifted index (LI) usually >-2 K] (Wakimoto 1985). The exact locations of these downburst winds are difficult to forecast since they are often formed by seemingly benign-looking clouds or reflectivity signatures (Mielke and Carle 1987; Meyers et al. 2006). Downbursts can be extremely hazardous for aircraft operations, especially during takeoffs and landings.

Hail and graupel (soft hail) is often found in convective precipitation over mountainous regions, in part, due to the relatively low freezing level above the ground compared to lower elevations. Severe hail can often occur adjacent to mountain locations such as the High Plains to the lee of the Rocky Mountains (Doswell 1980). For example, a hailstorm caused $350 million dollars in damage over the Front Range, in Denver, Colorado on 13 June 1984 (Blanchard and Howard 1986). Numerous severe hailstorms have also been documented to the east of the Canadian Rockies in Alberta, Canada (Wojtiw 1975; Smith and Yau 1987) and in central Switzerland near the Jura Mountains to the north and the Alps to the south (Houze et al. 1993).

1.2.8 *Cold-Air Pools and Air Quality*

Cold-air pools are not typically considered a "severe weather phenomenon", but their persistence can lead to poor air quality episodes in basins and valleys (also see Chaps. 2 and 5). The World Health Organization recently estimated that 800,000 deaths per year worldwide could be attributed to urban outdoor air pollution and the economic impact from air pollution-related illness is estimated at US $150 billion per year (World Health Organization 2002). Often these cold pools form in basins or within valleys with terrain constrictions that allow cold air to build up behind the constriction. The development of cold pools reduces the dispersion of air pollutants and adversely affects air quality. These poor air quality episodes are not restricted to large urban areas, but can occur anywhere where emissions are concentrated, such as in the lower end of the Colorado Gore Valley west of Vail or along the Mossau and Finenbach Valleys in Germany (Geiger et al. 1995; Whiteman 2000). Some of the highest particulate matter concentrations observed in the United States occur episodically in Logan, Utah, a mid-sized metropolitan area with a population of about 125,000 that is in the topographically confined Cache Valley (Malek et al. 2006). More recently, in the vicinity of the Jonah–Pinedale Anticline natural gas field, in the rural Upper Green River Basin of Wyoming, air quality instrumentation measured 8-h averaged ozone concentrations above the Environmental Protection Agency's threshold of 75 parts per billion (ppb). This criteria, which is more typical of summertime events, was exceeded on 14 days and resulted in the first ever wintertime ozone advisories in Wyoming (Schnell et al. 2009). The formation of diurnal cold-air pools and valley inversions has a potential secondary effect. It can also be a complicating factor in frost events, which can be problematic for agriculture at critical times of the growing season.

Degraded air quality due to mountain haze and pollutant transport can impact the tourism industry including the mountain vistas in national parks. Poor air quality degrades the majestic views on public lands, but also can negatively impact the long-term health of plants, trees and animals.

1.3 The Contemporary Forecast Process in Complex Terrain

At its core, weather forecasting is a scientific endeavor involving hypothesis formulation, hypothesis testing, and prediction (Roebber et al. 2004), and applying this scientific method is especially crucial over complex terrain. The forecaster must develop a conceptual understanding of the past and present weather, formulate hypotheses about why and how the atmosphere is evolving, and then seek evidence to confirm or reject the hypotheses. This iterative process continues and the hypothesis is refined until a prediction is made. Given the huge volume of data, analyses, and numerical forecasts available, the forecaster must employ rapid cognition, make quick decisions, and make judgments in the face of uncertainty

(Doswell 2004). When faced with a “firehose” of data, the ability of a forecaster to skillfully determine what is important is an example of what Gladwell (2005) described as “thin slicing”.

Klein Associates has studied the cognitive and psychological aspects of U.S. military meteorologists (Klein 1998; Stuart et al. 2007). They found distinct differences between inexperienced or non-engaged forecasters and the experienced or expert forecasters. The inexperienced forecasters typically relied too much on computer models and tended to be reactive with the forecasts. The experienced forecasters had a more global perspective and they tended to be more flexible with their tools and procedures, often relying on conceptual models in the forecast process. They typically employed a recognition-primed decision model (Klein 1998) which combines both analysis and intuitive methods (Doswell 2004) that allows the forecaster to absorb incomplete information under time constraints and arrive at proper forecasts. The expert forecasters draw from their vast forecast experience to arrive at their forecast decisions.

Bosart (2003) argues that the forecast process is most effective when the forecaster addresses six critical questions: (1) What happened? (2) Why did it happen? (3) What is happening? (4) Why is it happening? (5) What is going to happen? (6) Why is it going to happen? In an era of increasingly skillful numerical weather prediction models, it is easy for forecasters to concentrate only on question 5. Nevertheless, knowledge of the antecedent conditions and underlying physical processes is extremely valuable, particularly when the numerical guidance “goes awry” or is unable to resolve critical orographic effects (Bosart 2003; Dunn 2003).

Although there are a variety of forecasting styles (Pliske et al. 2004), skillful forecasting in mountainous regions typically requires: (1) a core understanding of synoptic scale and orographic processes, (2) careful evaluation of the evolving synoptic setting and flow interaction with the terrain, (3) knowledge of the advantages and limitations of the objective tools of forecasting over complex terrain, and (4) the subjective integration of these tools by the forecaster.

1.3.1 Scale Interaction: The Forecast Funnel

Forecasters commonly use the so-called *forecast funnel* to evaluate the synoptic setting and flow interaction with terrain (Snellman 1982; Horel et al. 1988; Steenburgh 2002; Dunn 2003). As illustrated conceptually by Fig. 1.5, the forecaster begins at the global or planetary scale, focuses attention on progressively smaller scales, and ultimately builds in the orographic effects at the local scale. The forecaster considers how the interaction of the large-scale or synoptic flow with the regional and local orography will influence weather locally. An important premise of the forecast funnel is that processes on each scale are dependent upon those at other scales. For example, in the case of orographic precipitation, the forecaster typically begins by evaluating the past, current, and future synoptic setting and

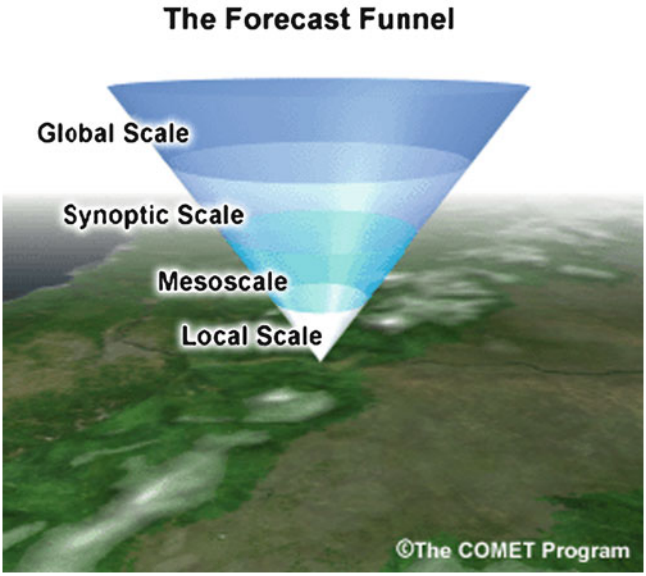

Fig. 1.5 The forecast funnel (Courtesy of COMET) (The source of this material is the COMET® Website at http://meted.ucar.edu/ of the University Corporation for Atmospheric Research [UCAR], sponsored in part through cooperative agreement(s) with the National Oceanic and Atmospheric Administration [NOAA], U.S. Department of Commerce [DOC]. ©1997–2010 University Corporation for Atmospheric Research. All Rights Reserved)

the large-scale characteristics of the airmass interacting with the topography. The forecaster will determine his/her confidence in the large scale forecast and if it is low, it will adversely affect his/her confidence in the forecast guidance on the smaller scales. As the forecaster examines the regional scales, parameters such as stability, temperature, humidity and wind and their influence on the terrain-induced flow and precipitation dynamics are considered. Finally, the forecaster will scrutinize the local scale to determine how the topography has influenced and will influence winds, moisture and precipitation distribution at a specific location. Local orographic and microphysical effects are considered at this level. This scale is the most difficult to address in an operational environment and requires reliance on pattern recognition and knowledge of the local climatology.

The forecast funnel in complex terrain requires a sound understanding of synoptic, mesoscale and mountain weather processes. It also requires the forecaster to recognize the advantages and limitations of the available observational and numerical tools and apply the proper forecasting techniques. Ultimately, the forecast funnel enables the forecaster to prioritize and assimilate the massive volume of geophysical and numerical data and to identify what is important on a day-to-day basis.

1.3.2 Objective Tools

The forecaster utilizes a number of objective analysis and forecast tools including in situ and remotely-sensed observations (also see Chap. 8) and numerical weather prediction models (also see Chaps. 9, 10, 11). Unique aspects of the use of these tools in complex terrain are described below.

1.3.2.1 Surface-Based Observations

A major challenge for weather analysis over complex terrain is the need for high-density surface observations to resolve the fine-scale gradients in surface weather produced by topographic forcing. As a result, forecasters desire as much observational data as possible and are willing to compromise, often relying on observations from heterogeneous networks with differing sensor types, biases and reliabilities (e.g., Horel et al. 2002). Some of the advantages of this approach include higher data density, higher frequency observations at some locations, and observations from non-conventional locations. Some of the disadvantages include non-uniform data and siting characteristics, stations that do not report the full suite of data, an increased need for quality control by the forecaster, and varying instrumentation with inconsistent averaging intervals. Another critical issue regarding surface observations in the mountains is the siting or microclimate where instrumentation is placed. For example, many Remote Automated Weather Systems (RAWS) (Myrick and Horel 2008) which are geared to fire weather observations are sited on south aspects to capture worst case scenarios with regard to fire weather applications. Geiger et al. (1995) showed that temperatures on south aspects in the midlatitudes are typically 3°C warmer than northern slopes due to sun angle. Most Snowpack Telemetry (SNOTEL) instrumentation, run by the USDA's National Resources Conservation Service, is sited on aspects more conducive for deeper snowpack and hydrological applications (Dressler et al. 2006). A failure to understand these types of differences can lead to unrealistic biases in analyses and forecasts. Additionally, incorrect or imprecise specification of the location of the instrumentation can negatively impact resolution of fine-scale features and model verification scores in complex terrain (Ludwig et al. 2006). The bottom line is that forecasters need to make sure their observational data is quality controlled and siting biases are taken into account.

Surface-based observations provide an added benefit after the event as well. Observations allow the forecaster to do post-analysis for verification and to conduct post-mortems of the event. This process is vital to understanding the physical controls of a particular storm or event. Observational data are also used as a "first forecast" to produce weather fields based on the previous day's observations through bias-corrected statistics.