CLIMATE CHANGE AND ASPEN:

AN ASSESSMENT OF IMPACTS AND POTENTIAL RESPONSES

A report of the Aspen Global Change Institute

Prepared for the City of Aspen

PREPARED BY:
Aspen Global Change Institute, Center of the American West, The Rural Planning Institute, Stratus Consulting Inc., & Wildlife & Wetland Solutions, LLC

ASPEN GLOBAL CHANGE INSTITUTE

Climate Change and Aspen:
An Assessment of Impacts and Potential Responses

A report of the Aspen Global Change Institute

Prepared for the City of Aspen

July 2006

PREPARED BY:

Aspen Global Change Institute

Center of the American West

Rural Planning Institute

Stratus Consulting, Inc.

Wildlife & Wetland Solutions, LLC

THE ASPEN GLOBAL CHANGE INSTITUTE

100 East Francis Street
Aspen CO 81611
http://www.agci.org
970 925 7376
agcimail@agci.org

OUR MISSION

The Aspen Global Change Institute (AGCI) is an independent, 501 (c)3 non-profit organization. Its mission is to further the understanding of Earth systems and global environmental change through interdisciplinary meetings, publications, and educational programs.

COVER PHOTO CREDITS

Front Cover

Powder Skier at Aspen Highlands:
Zach Ornitz / Aspen Daily News

Luke Wynen–2006 Winter X-Games Superpipe:
Zach Ornitz / Aspen Daily News

Grand Tasting Pavilion at the 2005 Aspen Food & Wine Magazine Classic:
Perry Johnson / Food & Wine Magazine

Back Cover

Trout:
Mark Fox / The Aspen Times

Kristina Koznick–2005 Women's World Cup at Aspen:
Mark Fox / The Aspen Times

This publication is part of the Aspen Global Change Institute's *Elements of Change* series.

Design by: max_ink [www.max-ink.net]
Layout & graphics by: Michelle Masone

ISBN 0-9741467-3-0

Authors by Chapter

CHAPTER 1
John Katzenberger
Kristine Crandall

CHAPTER 2
Joel Smith

CHAPTER 3
Brian Lazar

CHAPTER 4
Diana Lane
Jonathan Lowsky
Joel Smith

CHAPTER 5
Hannah Gosnell
Gabe Preston
Bill Travis

CHAPTER 6
John Rice
Jim Henderson
Brian Lazar
Bill Travis
Sue Bookhout

APPENDIX A
Joel Smith

APPENDIX B
Robert L. Wilby

APPENDIX C
Linda Mearns
Claudia Tebaldi

APPENDIX D
Tom M. L. Wigley

APPENDIX E
Joel Smith

APPENDIX F
Russel Jones
Brian Lazar

Assessment Team

HANNAH GOSNELL, Center of the American West
JIM HENDERSON, Stratus Consulting, Inc.
RUSSEL JONES, Stratus Consulting, Inc.
DIANA LANE, Stratus Consulting, Inc.
BRIAN LAZAR, Stratus Consulting, Inc.
JONATHAN LOWSKY, Wildlife & Wetland Solutions
GABE PRESTON, Rural Planning Institute
JOHN RICE, Stratus Consulting, Inc.
JOEL SMITH, Stratus Consulting, Inc.
BILL TRAVIS, Center of the American West
TOM M. L. WIGLEY, National Center for Atmospheric Research
ROBERT L. WILBY, Environment Agency of England and Wales
MARK WILLIAMS, University of Colorado at Boulder

National Advisory Panel

DAN CAYAN, University of California–San Diego/Scripps
HADI DOWLATABADI, University of British Columbia
NICHOLAS E. FLORES, University of Colorado–Boulder
JOHN HARTE, Rocky Mountain Biological Lab
LINDA JOYCE, USDA Forest Service
L. RUBY LEUNG, Battelle-Pacific Northwest Laboratories
MICHAEL C. MACCRACKEN, The Climate Institute
LINDA MEARNS, National Center for Atmospheric Research
GERALD MEEHL, National Center for Atmospheric Research
ROZ NAYLOR, Stanford University
RON NIELSON, USDA Forest Service
STEPHEN H. SCHNEIDER, Stanford University

Editorial Review Board

SUSAN JOY HASSOL, Climate Change Writer
STEPHEN H. SCHNEIDER, Stanford University
RANDY UDALL, Community Office of Resource Efficiency

Editorial Team

Senior Editor: JOHN KATZENBERGER
Associate Editors: SUE BOOKHOUT
MICHELLE MASONE
KRISTINE CRANDALL
Assistant Editor: HILARY STUNDA
Data Compilation & Representation: MICHELLE MASONE

ACKNOWLEDGEMENTS

Many individuals and organizations contributed to the development of this report through their expert advice, data, reviews, & financial support. We gratefully acknowledge the contributions of:

Additional Research Contributors

Craig Anderson at Stratus Consulting for running the SNTHRM models; Andrew Klotz at the Rural Planning Institute for his assistance on Chapter 5; Carolyn Wagner at Stratus Consulting for her assistance on Chapter 2; and Mark Williams at the University of Colorado at Boulder for his work on Chapter 3.

City Of Aspen Staff

Steve Barwick, City Manager; Lee Cassin, Director of the Environmental Health Department; Stephen Kanipe, Chief Building Official; Mary Lackner, GIS Manager; Dan Richardson, City Global Warming Project Manager; and John Worcester, City Attorney.

Local Stakeholders

The local stakeholders who attended the June 2005 and January 2006 meetings, and in particular those individuals who donated their time for interviews: Gary Beach, Tom Cardamone, Sharon Clarke, Bob Harris, Connie Harvey, Tim Heng, Andrea Holland-Sears, Doug MacKenzie, Phil Overeynder, Steve Sewell, and John Upthegrove.

Modeling

Claudia Tebaldi and Linda Mearns at NCAR for providing the PCMDI modeling; Ruby Leung at Battelle-Pacific Northwest Laboratoriesfor providing the RCM modeling. The international modeling groups for providing their data for analysis, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for collecting and archiving the model data, the JSC/CLIVAR Working Group on Coupled Modelling (WGCM), and their Coupled Model Intercomparison Project (CMIP), and Climate Simulation Panel for organizing the model data analysis activity, and the IPCC WG1 TSU for technical support. The IPCC Data Archive at Lawrence Livermore National Laboratory is supported by the Office of Science, U.S. Department of Energy.
Gerald Meehl and Haiyan Teng at NCAR for providing the North American temperature and snow plots.

Other Contributors

Chris Pyke and Gene Reetz from the EPA; David Eskew from TN&A; Nelson Havey, AGCI Summer 2005 intern; and Colin Laird, Roger Pulwarty, Brad Udall, and Klaus Wolter for their much appreciated expert input.

The Aspen Global Warming Alliance

The City of Aspen, Community Office of Resource Efficiency, AGCI, The Aspen Institute, Aspen Skiing Company, Rocky Mountain Climate Organization, New Century Transportation Foundation, Holy Cross Energy, Rocky Mountain Institute, Aspen Center for Environmental Studies, Susan Joy Hassol, and Climate Mitigation Services.

Funding

The City of Aspen for providing the funds for this report; and the EPA for providing funds to TN & Associates allowing additional research on surface water resources by Stratus, CAW, and AGCI.

TABLE OF CONTENTS

TABLE OF CONTENTS

BY MAYOR HELEN KLANDERUD

THE CITY OF ASPEN
OFFICE OF THE MAYOR

July 12, 2006

In 2004, the Aspen City Council made a commitment to achieve the highest level of environmental protection for our beautiful valley and its quality of life. The council directed city staff to come forward with ideas and proposals to achieve this standard. John Worcester, Aspen City Attorney, presented an ambitious proposal he named "The Canary Initiative." The Canary Initiative identifies Aspen and other mountain communities as the canary in the coal mine for global warming. Aspen's goal: to aggressively reduce its contribution to global warming, and to engage other communities to send a clear message on the importance of this issue.

Data for the past 50 years collected at Aspen's weather station, and compiled by the city's environmental health department indicates a trend toward longer summers, shorter winters, and fewer days with below freezing temperatures. This data does not cover a sufficient time-period to make reliable conclusions about future climate or precipitation trends, nor do we know what effects a continuing trend in global warming will have on Aspen. However, the City of Aspen believes it is better to learn now rather than later, perhaps too late, what the possible effects of global warming on Aspen might be, and to do what Aspen as a community can do to reduce its greenhouse emissions.

This climate impact assessment represents a vital component of the Canary Initiative. It provides a scientific basis for assumptions about our future climate, and in conjunction with the greenhouse gas emissions inventory, will guide us in the implementation of actions to reduce Aspen's greenhouse gas emissions – our Canary Action Plan. Previous studies have indicated higher temperatures could have a substantial impact on our snowpack, our forests, and our rivers. This assessment provides information we need to consider ways to make Aspen's human and ecological communities more resilient to changes likely to occur.

In July 2005, Aspen was honored with an invitation to the first annual Sundance Summit – A Mayors' Gathering on Climate Protection. Mayors were invited based upon which cities will facilitate the greatest impact on global warming, provide broad geographic representation, and bring new voices to the table. Of the 45 U.S. mayors in attendance, representing 28 states and 10 million people, Aspen was the smallest city present. In 2003, the City of Aspen signed the U.S. Mayors' Statement on Global Warming, and in 2004, the Declaration of Energy Independence, a declaration signed by cities and Indian tribes to promote renewable energy and the development of wind turbines on Indian reservations. In 2005, on behalf of the City of Aspen, I signed the U.S. Mayors Climate Protection Agreement. Aspen is a member of the Chicago Climate Exchange and the Rocky Mountain Climate Organization.

Aspen is proud to be a leader in the pursuit of renewable energy to reduce greenhouse gas emissions. In

2005, over 50% of our electricity was produced from renewable resources. Today, we estimate it to be 75%. Aspen accomplished this while maintaining one of the lowest electric rates in the state. For its commitment to renewable energy Aspen received the World Wildlife Foundation's 2005 Power Switch! Pioneer award for its dedication "to addressing climate change by committing to a clean energy future."

The completion of this impact report is another milestone in Aspen's efforts to fight global warming. We have a long way to go, but we have taken the first steps, and will continue to take the necessary steps to meet the global warming challenge - a challenge unlike any other. If we are to leave our children and grandchildren a livable planet, we must commit ourselves to this challenge.

Mayor Helen Kalin Klanderud
City of Aspen

John Worcester, Aspen City Attorney contacted me in December of 2004 with an idea. John's idea was the Canary Initiative, a plan to place Aspen squarely among the growing number of cities not only concerned about climate change, but also taking action. He asked if I thought the Initiative was a good idea. I said it was and suggested the importance of several components: a thorough emissions inventory of Aspen and the surrounding area, by sector, with reduction goals; a climate impact assessment looking at changes to the climate, ecosystems, and socioeconomics; and, the need for education and public outreach. Over the following few months, we met with members of city council, the city manager and the mayor to develop the idea further. An alliance of organizations and individuals was formed to advise the city process.

John and city staff developed the idea into a resolution that was unanimously passed by the city in March 2005. The resolution called for:

- The creation of The Global Warming Alliance – a group of organizations and individuals to advise the city regarding the initiative
- An assessment of the impacts of climate change specific to the Aspen area
- A detailed emission inventory by sector to serve as the basis for tracking future emissions against a baseline
- The need to set emission reduction goals (Canary Initiative Action Plan)
- The creation of a city staff position to manage the Canary Initiative activities and engage the public
- An international conference on global warming, and
- A new hydroelectric plant on Maroon Creek to provide renewable electricity to the city.

The city's Canary Initiative website has information about these activities (www.canaryinitiative.com).

By summer of 2005 the city had contracted with Climate Mitigation Services to develop a greenhouse gas emissions inventory for the Aspen area, it had hired Dan Richardson as Global Warming Project Manager, and contracted with the Aspen Global Change Institute (AGCI) to put together a study team to assess and report on the impacts of climate change on Aspen.

The challenge of reporting on the diverse topics of climate, ecosystems and socioeconomics required the establishment of a broad working team. It consists of the University of Colorado's Center of the American West (CAW), Stratus Consulting, Inc., the Rural Planning Institute, and Wildlife & Wetland Solutions, LLC. The study team was further guided by a national panel of scientists, an editorial review board and the input of stakeholders from Aspen and the Roaring Fork Valley.

Time and resources dictated that the study focus on climate change impacts on skiing. The study area was set as the watershed above the confluence of Woody Creek and the Roaring Fork River. While skiing was recognized as central to the study, stakeholder input identified impacts related to streamflow as a key priority. This led to the pursuit of additional resources to broaden the scope of the study. The contract with the City was augmented by a grant from the Environmental Protection Agency managed by TN & Associates, Inc. The EPA grant provided funds to add a streamflow component to the study coupled with a set of stakeholder interviews regarding present and future uses of the river including the effect of projected climate change. CAW, Stratus, TN&A and AGCI are participating in the EPA sponsored work included here in Chapter 6.

John Worcester's idea has rapidly taken root. Other municipalities are inquiring about how they can do something similar, businesses and citizens are becoming engaged through outreach efforts. Results from the climate study are being presented at conferences and are being prepared for submission to scientific journals. City council will soon have the opportunity to vote on the Canary Action Plan and set in motion a strategy for carbon emission reductions.

The Canary Initiative has benefited greatly by the City of Aspen's longtime commitment to environmental issues including initiatives preserving open space, its aggressive stance on air quality, its energy building code, establishing an Ecological Bill of Rights as a guiding principle, investments in renewable energy systems, and its support of mass transit.

The city is not alone in fostering a strong environmental ethic. The Aspen Skiing Company, as Aspen's key resort industry, is recognized as a leader in the industry for its environmental achievements and progressive stance on climate change. The Colorado Climate Project, a program of the Rocky Mountain Climate Organization, is working to reduce Colorado's contribution and vulnerability to climate disruption by developing and getting implemented an action agenda, to be presented to state and local governments; the project is the first of its kind to be undertaken as a private initiative. Other non-profits such as the Community Office of Resource Efficiency, the Rocky Mountain Institute, the Aspen Center for Environmental Studies, the Roaring Fork Conservancy, and the Rocky Mountain Climate Organization have environmental protection and sustainable communities central to their mission. These environmental organizations joined with Holy Cross Energy and the Aspen Municipal Electric utility and others to serve on the Aspen Global Warming Alliance providing guidance to the Canary Initiative.

The Canary Initiative is truly a private-public partnership aimed at taking an informed look at the consequences of global warming, quantifying emissions and their sources, and setting reduction targets while recognizing that actions taken now locally – from the bottom-up, community by community, and globally from the top-down – together can greatly reduce future impacts.

John Katzenberger
Director
Aspen Global Change Institute

Climate change is happening globally, regionally, and locally. The amount and rate of change will increase if we stay on our present course. A low greenhouse gas emissions path will make a tremendous difference to future climate well past the 21st century. Local choices can partially reduce Aspen's vulnerability to climate change. Aspen's diverse economy in both the summer and winter will become increasingly important as winter recreation is compromised by a warmer world.

OVERVIEW

Aspen's climate is changing. And greater change is projected with much higher temperatures. Some future scenarios result in temperatures high enough to end skiing on area mountains. How much warmer it gets, and the extent of impacts, depends on the global emissions of greenhouse gases, the climate system's response to those gases, and society's ability to adapt to change. Climate modeling in this report indicates that if communities and nations of the world choose to pursue a low emissions path, the change in Aspen's climate by the end of this century will be less severe, maintaining conditions closer to our present climate.

Projected Change in Temperature by 2030 and 2100
in Degrees Fahrenheit

	Low Emissions	Medium Emissions	High Emissions
2030	—	3.2 to 4.5	—
2100	5.2 to 7.7	7.0 to 10.6	11.3 to 16.9

TABLE ES.1: **Regional climate projections for the Southern/Central Rockies applied to the Aspen study.** Shown are projected ranges of temperature change (in ºF) by 2030 and 2100 for 5.4ºF (3ºC) sensitivity to doubling CO_2. Note: temperature ranges for the low and high emissions scenarios are not shown for 2030 because the emissions scenarios do not diverge significantly until after 2030.

This report examines potential impacts to, and vulnerabilities of, area ecosystems, socioeconomics, and climatic conditions. The emphasis of this study is on how mountain snow may change and the subsequent cascade of impacts. Adaptations can be employed to reduce vulnerability to some impacts, particularly in the highly managed and built environment. Impacts to plant and animal communities, water resources, and recreational and cultural pursuits cannot be avoided; however, the extent of these impacts can be greatly reduced by a low emissions path and adequate planning and implementation of necessary adaptations.

THE CANARY INITIATIVE

In March 2005, the City of Aspen unanimously passed a resolution called The Canary Initiative. The Canary Initiative is a direct result of one community doing its part to reduce greenhouse gas emissions (GHG) locally, while fully understanding that global warming is an international issue that can only be solved by the joint effort of many communities working together. The first step in the Canary Initiative, an Aspen GHG emissions inventory, is complete (Heede, 2006). The next step is to develop emission reduction goals that can be matched to sectors of the community such as transportation and buildings.

These goals will be formalized in the City's Canary Action Plan, currently in draft stage. [1]

In addition to an emissions inventory and action plan, the resolution called for:

> *…a comprehensive integrated scientific assessment specific to the Aspen area on the likely consequences to Aspen of global warming over the course of the 21st century.*

This report provides the results of the assessment and is the culmination of over a year's work by the assessment team with input from stakeholders, city staff, and the national advisory panel.

REPORT ORGANIZATION AND METHODS

This assessment starts by reviewing trends in current climate and exploring possible future climates. We narrowed the range of options by focusing on a low, medium, and high projection of future greenhouse gas emissions (which also allowed us to examine the benefits of reducing emissions), by choosing models with similar sensitivities to greenhouse gas warming, and choosing models that most accurately simulate the current climate of the interior North America. Because the global models operate at large spatial scales, we also applied a statistical downscaling method to one scenario and examined results from a regional climate model in order to concentrate our analysis on the Aspen area.

Climate models from several major climate centers, such as the National Center for Atmospheric Research and the Max Plank Institute, were utilized to project changes in monthly temperature and precipitation by 2030 (near term) and 2100 (long term). The results of the climate modeling were then used to examine how a changing climate will affect snow – both its quality and quantity. The socioeconomic implications of an altered snowpack, particularly in relation to skiing, are central to this analysis. The climate model output is also utilized in an analysis of the effects of climate change on ecosystems, exploring potential impacts on life zones, fire, and pests. The report concludes with a discussion of the Roaring Fork River, and how it may be altered by climate change, historical river uses, and how present stakeholders, both appropriators and instream users, may respond to these projected changes.

GREENHOUSE GAS EMISSIONS SCENARIOS

Fundamental to a climate impact assessment is how much the Earth's climate will be forced to change by human contributions to greenhouse gas concentrations.[2] To assess the potential impacts of climate change on Aspen, we selected a standard low, medium, and high GHG emissions scenarios based on the work of the Intergovernmental Panel on Climate Change (IPCC, 2000a). Each of the scenarios take into consideration future change in human population, economic growth, the energy efficiency of the economy and the carbon intensity of energy. The emissions scenarios are utilized in climate models to produce projections of possible future climate. These emissions paths are the sum of the choices we make everyday, from land-use decisions to how we provide energy for our homes and vehicles.

---

1. Even before the emission reduction plan will go into effect, Aspen has worked to reduce its energy footprint. Examples include the city electric utility providing about 78 percent of its electricity from renewable sources, adopting progressive energy components of its building code, establishing the Renewable Energy Mitigation Program – a tax on carbon emissions, joining the Chicago Climate Exchange, and working with area governments to establish a valley-wide mass transit system.

2. The primary emissions scenarios used in this report are the IPCC Special Report on Emissions Scenarios (SRES) standard scenarios B1 (low), A1B (medium), and A1FI (high). Some of the model runs utilize B2 (medium low) and A2 (high).

The IPCC primary group of emissions scenarios used by climate modelers are plausible representations of how the world may change. They do not include policy intervention. It is possible that more aggressive reductions in greenhouse gas emissions could be achieved, resulting in total emissions by the end of this century below the relatively "green" B1 scenario used in this analysis.

CLIMATE CHANGE AND ASPEN

Climate

An example of how a warming trend is already affecting Aspen is the increase in frost-free days per year since the 1950's. This trend is particularly important to ecosystem function and in agricultural applications from backyard gardens to ranching operations. A change in frost-free days is critical to ski mountain managers; a loss of temperatures below freezing in the fall directly affects snowmaking opportunities prior to opening day.

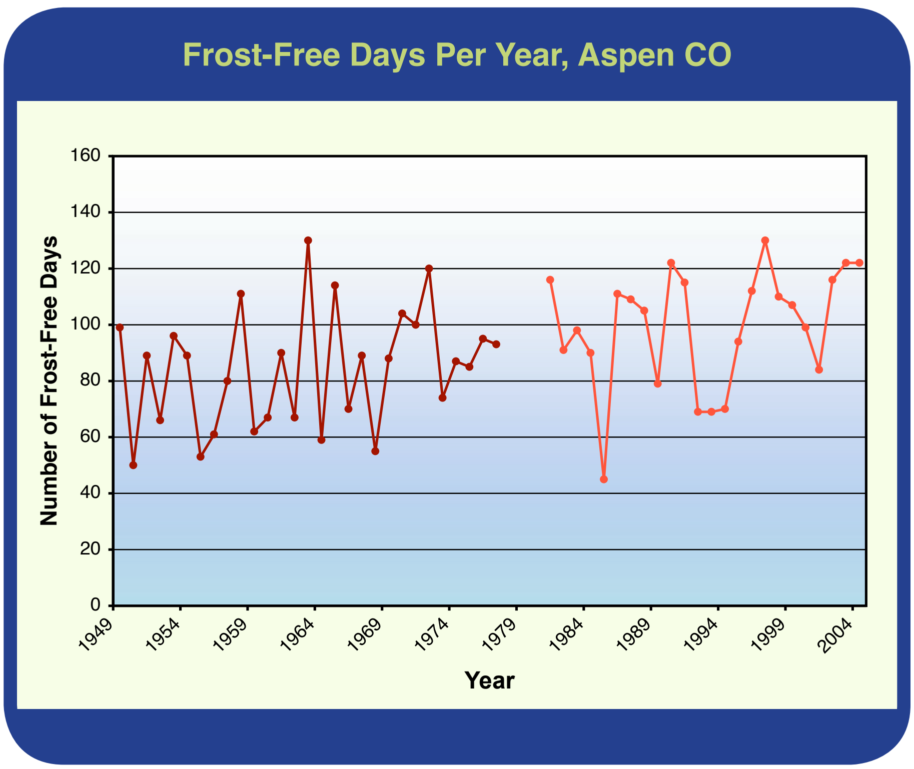


FIGURE ES.1: **Frost-free days per year in Aspen as recorded at the Aspen National Weather Service Cooperative Network Station, 1949-2004.** (Note: The Aspen weather station was moved in 1980 from an in-town elevation of approximately 7945 feet to 8163 feet at the Aspen Water Treatment Plant. Dark red represents data from the old Aspen station. Light red represents data from the current Aspen 1 SW station.)

The following set of figures (ES.1- 4) show regional temperature and precipitation change applied to Aspen with the medium emissions scenario by 2030 and 2100 from a 5 multimodel set of runs. The range in each bar represents the hottest and coolest, and wettest and driest, of the five models. The monthly mean of the 5 models is represented as a horizontal line in each bar. Projections of change in precipitation are more variable than temperature. By 2100 the models diverge in projecting more or less precipitation, but show a slight decrease from present conditions on an annual basis.

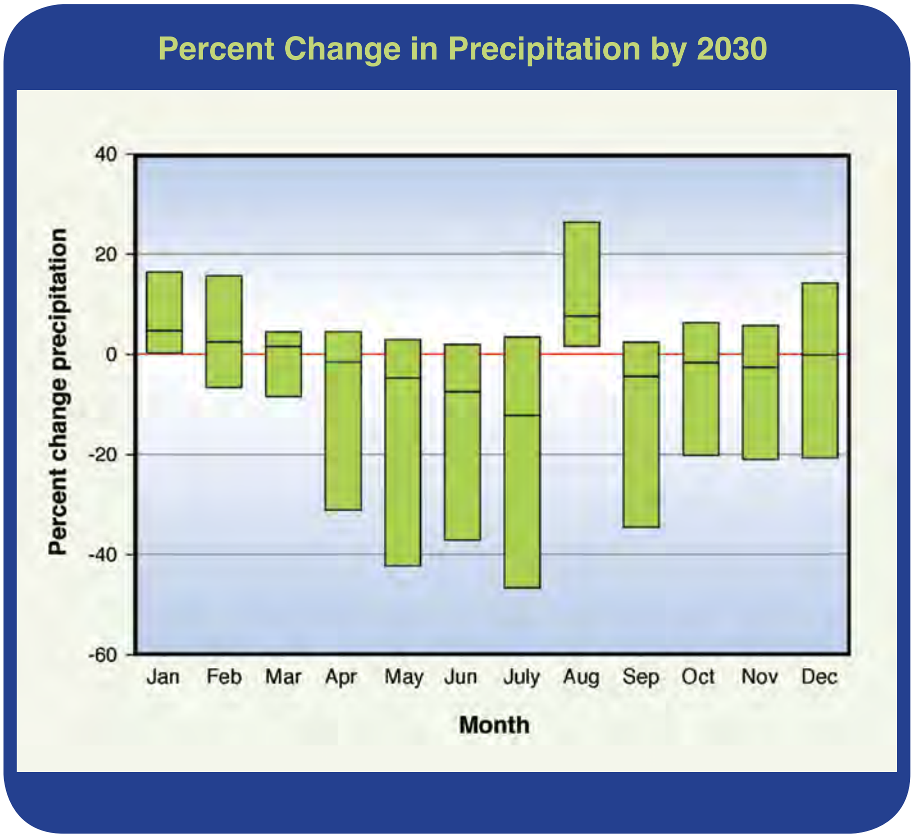


FIGURE ES.2: **Projections for percent change in monthly precipitation by 2030 under a medium emmisions scenario (A1B) for the Southern/Central Rockies applied to Aspen.** Each box plot represents the maximum (top of box), average (center line), and minimum (bottom of box) of a five model set.

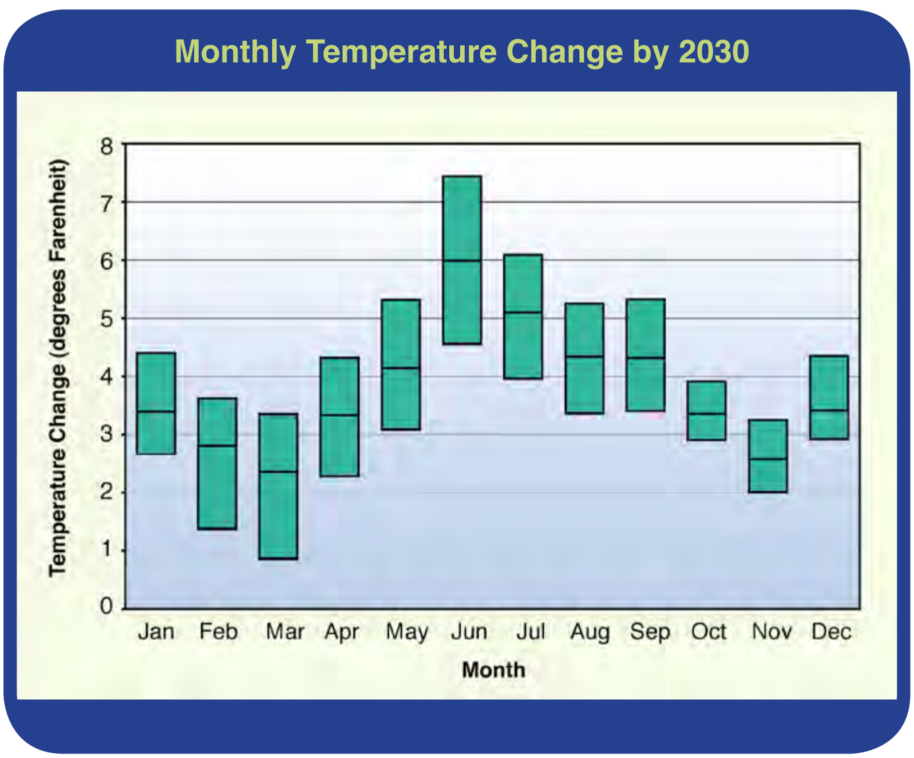


FIGURE ES.3: **Projections for monthly temperature change by 2030 under a medium emmisions scenario (A1B), in degrees Farentheit, for the Southern/Central Rockies applied to Aspen.** Each box plot represents the maximum (top of box), average (center line), and minimum (bottom of box) of a five model set.

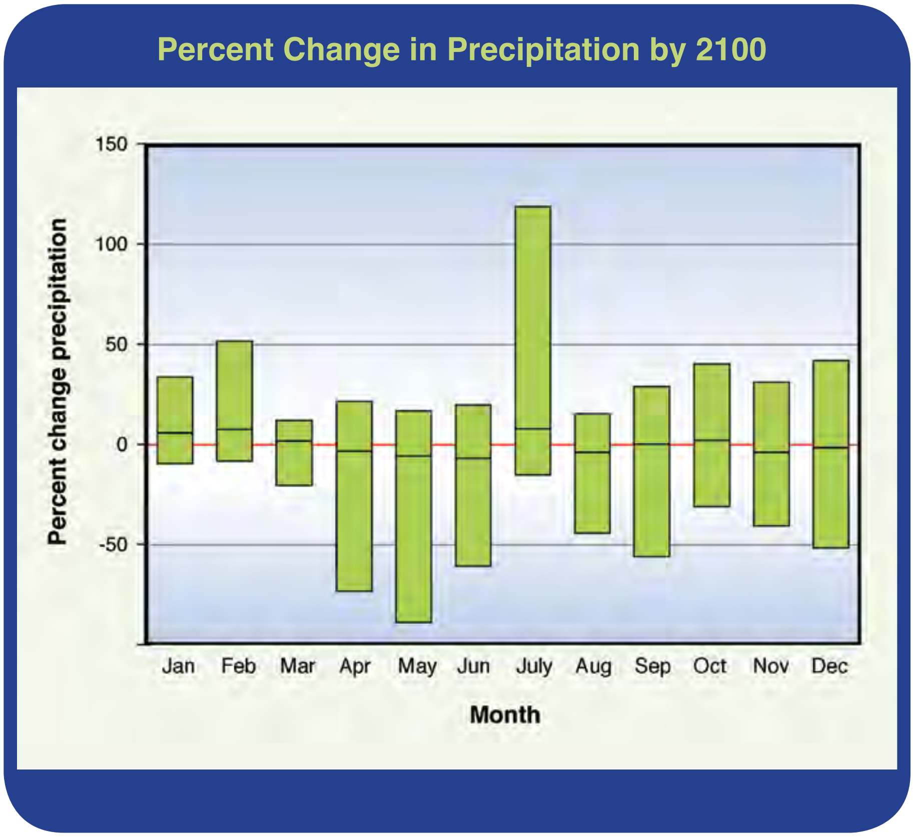


FIGURE ES.4: **Projections for percent change in monthly precipitation by 2100 under a medium emmisions scenario (A1B) for the Southern/Central Rockies applied to Aspen.** Each box plot represents the maximum (top of box), average (center line), and minimum (bottom of box) of a five model set.

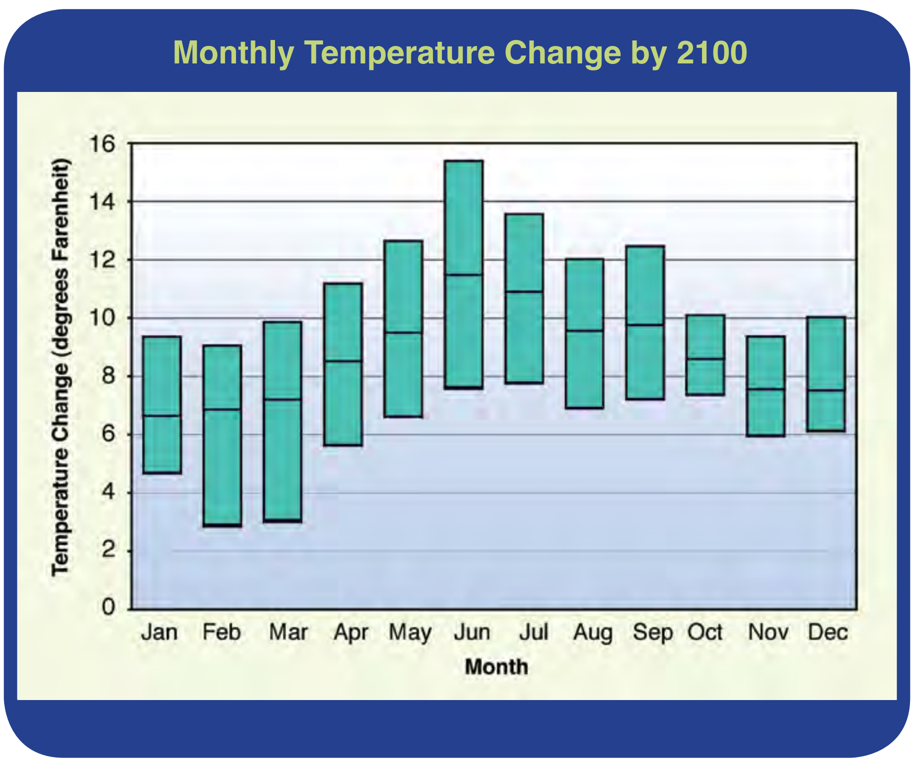


FIGURE ES.5: **Projections for monthly temperature change by 2100 under a medium emmisions scenario (A1B), in degrees Farenheit, for the Southern/Central Rockies applied to Aspen.** Each box plot represents the maximum (top of box), average (center line), and minimum (bottom of box) of a five model set.

All of the models and modeling approaching utilized in this assessment project increasing average annual temperatures for the Aspen area over the course of 21st century, although the magnitude of projected change in temperature or precipitation is not uniform throughout the months of the year. The following set of figures show the monthly mean (horizontal line within each bar) for 2030 and 2100 under the middle emissions scenario. The range in each bar represents the hottest and coolest, and wettest and driest, of the five models used.

The output of these model runs are applied in Chapter 3 to analyze change in snow conditions and snowpack and how an altered snowpack affects streamflow. The streamflow analysis indicates a reduced snowpack with more precipitation falling as rain rather than snow. Peak runoff is likely to occur earlier in the year – approximately one month – while total runoff is less certain.

Ecosystems

Higher temperatures will also affect upper Roaring Fork ecological communities. The montane, subalpine, and alpine zones evident when traveling from the Woody Creek area into Aspen and up to Independence Pass, will move up-slope to higher elevations. As the climate changes at rates faster than those seen in the last 8,000 years, plant and animal communities will be forced to adapt to changing conditions. This process may take hundreds of years and will likely produce plant and animal communities unlike the ones that have been common to the Aspen area since it was first settled. Ecosystem stress and higher temperatures will likely increase the risk of fire and insect outbreaks.

Species at the highest elevations will be most vulnerable to climate change. Species loss is expected. For example, studies have found that higher stream temperatures associated with global warming projections would result in a loss of habitat for cold temperature dependent species such as trout, and a gain in habitat for warmer tolerant and exotic species (IPCC, 2001a; Wagner, 2003). The combination of fragmented habitats and climate change is a synergisticproblem for migration and relocation of species. Plants and animals need suitable habitat and a way to get there in response to the forces of global warming. Mountain peaks become isolated islands exacerbating the problem.

Socioeconomics

Projected growth in Aspen's economy and population indicate the next generation of visitors will experience a more diverse economy and set of cultural experiences than today. The percentage of Aspen's economy associated with skiing will likely decrease, regardless of climate change, because of greater growth in other areas. On-mountain adaptations to changing climate and snow conditions are potentially costly, but will likely maintain skiing as a central part of Aspen's economy – at least for several decades. Should the world maintain a fossil fuel-intensive, high emissions course, skiing as we know it will be in jeopardy by the end of the century.

SUMMARY

Numerous studies indicate the world is committed to a certain amount of human-caused climate change from the amount of GHGs already in the atmosphere. It is up to our actions as individuals, and as nations, to determine whether or not the additional change that unfolds in this century is great or small. Locally, Aspen has an opportunity not only to extend its mitigation plans – thereby reducing its own contribution to climate change, but also to consider ways to adapt to climate change that are anticipatory rather than reactive.

The following section outlines the key findings from the climate, ecological and socioeconomic elements of this assessment.

Key Findings: Climate

Global CO_2 concentrations before the Industrial Revolution stayed about the same for thousands of years. Since the late 1800s, global CO_2 concentrations have increased by about 35 percent. These increases have caused the globe to warm, and projections indicate greater warming is in store at an increased rate. The high, medium, and low greenhouse gas emissions scenarios used in this study have similar emissions levels in 2030, but then they diverge, resulting in drastically different concentration levels and climate projections by 2100.

Trends for the Aspen area's climate over the past 25 years:

- While highly variable, total precipitation has decreased 6 percent and the amount falling as snow has decreased 16 percent. At 10,600 feet (3,231 m) elevation, total precipitation has decreased 17 percent.
- Average temperatures have increased about 3.0°F (1.7°C)
- The number of frost-free days per year, although highly variable, on average has increased about 20 days.

Projections for changes in Aspen's climate by the year 2030:

- By 2030 the middle emissions scenario average temperatures are projected to increase by 3 to 4°F (1.7 to 2.2°C) over what they were in 1990.
- Precipitation change is less clear than temperature change. The multimodel averages project a slight decrease or no change in precipitation by mid- to late century.

Key Findings: Climate

Projections for changes in Aspen's climate by the year 2100:

- Model projections of seasonal change indicate greater increase in summer vs. winter temperatures – contrary to previous assessment mid-continental change patterns.

- More of Aspen's annual precipitation will likely fall as rain rather than snow.

- Spring run-off is very likely to occur earlier. There is also a medium probability of mid- to late winter partial thaws and rain events. Reaches of the Roaring Fork River system already seeing difficulty in achieving minimum streamflow due to diversions and drought years will be further stressed by global warming. Reaches without minimum stream flow stress today will likely experience stress in the future.

- A future world that follows a low greenhouse gas emissions scenario (such as B1) is projected to substantially reduce the impacts of climate change on Aspen's climate, ecological systems, and recreational amenities.

High greenhouse gas emissions scenarios (A1FI) are likely to end skiing in Aspen by 2100, and possibly well before then, while low emission path scenarios preserve skiing at mid- to upper mountain elevations. In either case, snow conditions will deteriorate in the future.

- The ski season will start later and end earlier (2030 and 2100).
- Early season snow depths will be reduced (due to more precipitation as rain).
- Spring melting will begin earlier.

Photo Credit: *Traffic on Highway 82*, Paul Conrad / The Aspen Times

Key Findings: Climate

- Maximum snowpack (i.e. the date when melting begins) will occur in early February under the middle (A1B) and high (A1F1) emissions scenarios (compared with March presently).
- By 2100, there will be no consistent winter snowpack at the base of the ski areas except possibly under the lowest greenhouse gas concentrations (B1) scenario.
- Snow quality will likely degrade more in the spring than fall.
- Under the highest emissions scenario, no skiable snow will exist at the base by 2100.

Snowmaking has been an important hedge against climate variability. Its feasibility in the future involves several challenges/questions:

- Increased temperatures will require increased energy use to produce snow.
- Undertaking more snowmaking will require additional water, a resource that will become increasingly valuable for other uses.
- Warmer pre-season and early season temperatures will reduce snowmaking opportunities.
- Reliable opening day schedules will be pushed further into the winter.

Photo Credit: *Snow Maker at Pitztal* © The Canary Project / Susannah Sayler & Edward Morris, www.canary-project.org

Key Findings: Ecology

With a warming climate, some plant communities in the Roaring Fork Watershed will move to higher elevations.

- In terms of vegetation, Aspen is likely to begin to look more like the mid-Roaring Fork Valley area.
- Plant and animal species most at risk of diminishing due to global warming are those at higher elevations, such as alpine meadows and sub-alpine forest communities, because of decrease in average snowpack, earlier bare ground and diminishing migration routes at higher elevations.
- Present plant communities in the Aspen area's alpine zone are very likely to diminish and some are likely to disappear over time.

Climate change affects the frequency and size of wild fires in first half of the 21st century.

- With no fire suppression, modeling projects larger average and maximum fire size compared with a scenario that included fire suppression policies.
- With fire suppression, the average fire size is projected to be approximately 50 percent larger than the historic size.

Key Findings: Ecology

Climate change increases the likelihood of insect outbreaks and invasive plant species.

POTENTIAL CHANGES ARE:

- Spruce-fir forest become more vulnerable to spruce beetle infestations, through increased temperatures and periodic drought from climate change.
- Aspen stands will become susceptible to gypsy moth invasions.
- Higher temperatures mean lower overwinter mortalities that keep insect populations in check. Increased summer warming could allow insects to complete a lifecycle in a shorter period of time, resulting in an increased risk of massive outbreaks.
- Higher concentrations of atmospheric CO_2 give some non-native invasive plants an advantage, while increased temperatures place additional stress on competing native vegetation. More invasive plant species are likely to out compete native vegetation.

Given complex interactions and interconnections between plant and animal communities, it is hard to predict detailed adaptation responses or likelihoods of extinction.

Key Findings: Socioeconomics

Current socio-economic trends for the Aspen area indicate an increasingly diversified regional economy, along with significant population increases. This will increase options for adapting Aspen's economy to changing conditions. Aspen's diverse economy, with its wide range of summer and winter cultural and recreational amenities, is likely to fare better than other, less diverse mountain resorts. Many part-time residents already rate summers as an important reason for living in the Aspen area. Still, skiing is important to the community, and it may be difficult to maintain a ski economy if global warming continues over the next century. Furthermore, other North American resorts, with access to higher elevation or higher latitude and colder ski terrain, will likely emerge as major competitors, while some resorts will suffer greater loss of snowpack than Aspen.

It will be important for the ski industry and community as a whole to explore a variety of strategies for adapting to climate change as it plays out over the next few decades.

EXAMPLES INCLUDE:

- Expand snowmaking area/capabilities to fully take advantage of cold temperature snowmaking opportunities.
- Adjust grooming techniques.
- Explore the use of higher ski terrain.
- Market the middle of the season.
- Expand non-snow winter recreation and cultural activities.

Climate change is likely to be progressively more problematic to the ski industry as the century progresses.

ECONOMIC ACTIVITIES THAT ARE SENSITIVE TO CHANGES IN SKIER VISITS INCLUDE:

- Direct ski operations
- Businesses serving skiing
- Residential investments (e.g. second homeowners).

Key Findings: Socioeconomics

Projected changes in the hydrograph are likely to affect municipal, agricultural, and recreational water users.

Municipal

Even with controlled growth, municipal services will need to continue to expand, and the potential for water shortages will likely increase.

Agriculture

- Earlier peak run-off means the majority of water will come at a time when hay fields, crops, and turf grass are not ready to start growing. Those without storage must consider how to use the peak run-off when it comes.

- Soils and vegetation may become drier. Thus, increased initial irrigation on hayfields may be required, which could lead to increased pressure on water resources.

- Mid-summer droughts will result in agricultural losses and costly turf loss.

Commercial Rafting

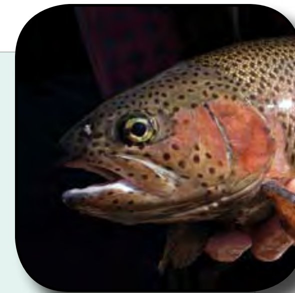
Significantly reduced flows in June 2100 would reduce the rafting client base of the upper Roaring Fork River.

- Peak runoff earlier in the spring will result in a shorter rafting season that starts earlier, at a time when there are few tourists in town. Rafting clients arriving later in June or July may be forced to find other recreational activities or access rafting opportunities downstream on the lower Roaring Fork or the Colorado River.

- Busing from the upper Roaring Fork will result in a higher cost to the business and the customer, as well as more fossil fuels burned.

Photo Credit: *Irrigating*, Mark Harvey

Key Findings: Socioeconomics



Recreational Fishing

- Lower flows in June and July and increased water temperatures (as a result of lower volumes, loss of stream cover, and warmer air temperatures) could have adverse effects on trout spawning, stream insect development, and trout survival.
- Fisherman would be forced to modify their schedules to accommodate changing river conditions.
- Low flows can cause a shift in people's perceptions: fishing outfitters in the Roaring Fork Valley would need to increase their marketing budgets.

Photo Credit: *Trout*, Mark Fox / The Aspen Times

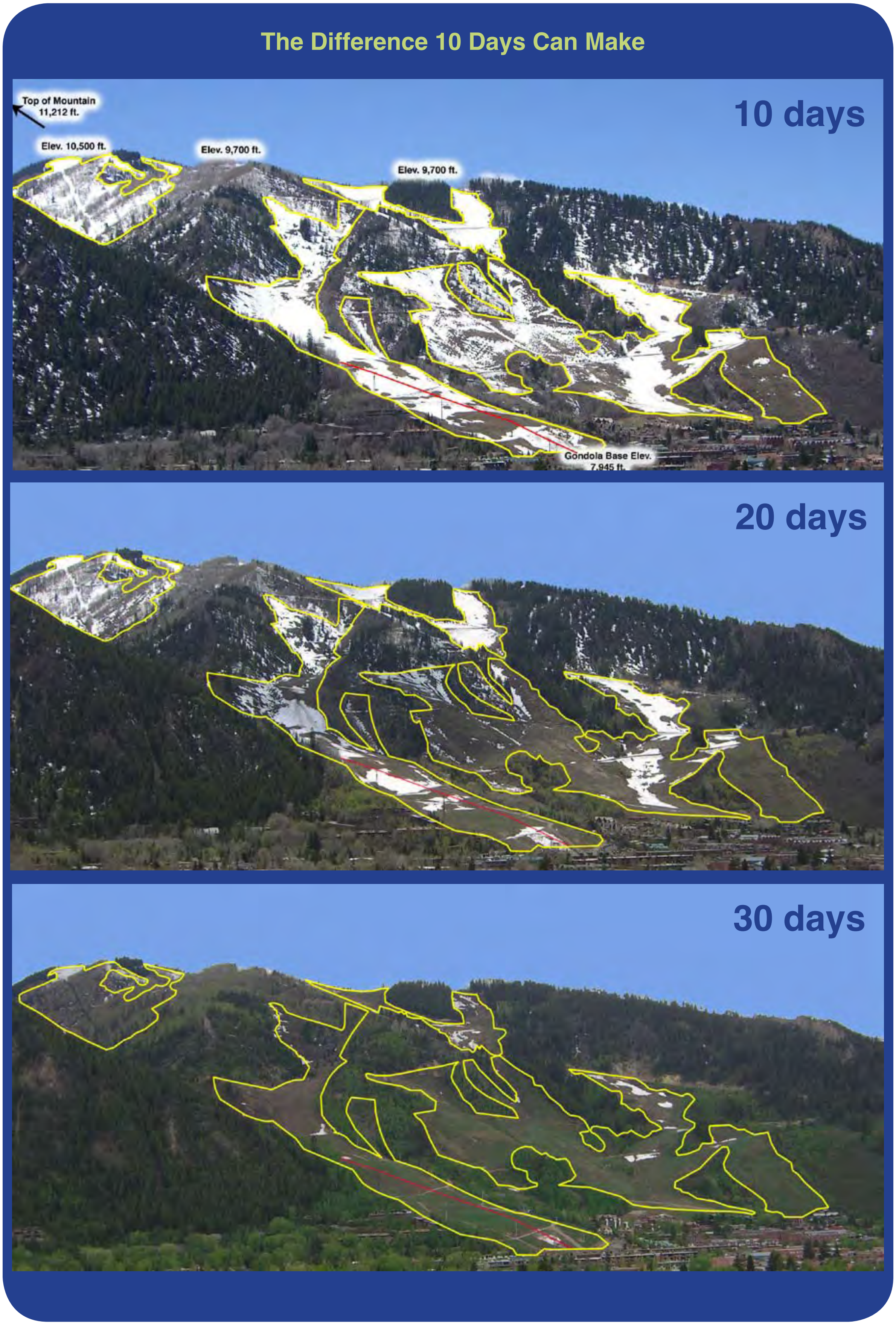


FIGURE ES.6: **The difference 10 days can make.** Three views of Aspen Mountain taken from Smuggler Mountain 10, 20, and 30 days after closing-day April 16, 2006. On closing day, the Aspen Skiing Company reported 100 percent of beginner and 97 percent of advanced and expert terrain open. The photos – with skiable terrain outlined in yellow and lower stretch of the gondola indicated in red – serve as an impressionistic view of how mid-April may appear in the future as temperatures increase. "Impressionistic" because it doesn't reflect any ski area management of snow cover, and the sun-angle in late April and early May is somewhat higher than it is earlier in April and late March by about 3 to 4 deg of altitude per 10 days. These photos are suggestive of the difficulties mountain managers may face in keeping the ski area open in coming decades.

1. INTRODUCTION

1.1 THE ASSESSMENT'S BOUNDARIES & EMPHASIS

In conversation 15 years ago, noted scientist Stephen H. Schneider turned the popular adage on its head when he said, "Think locally, act globally." What he was conveying is that climate change and other global scale changes attributed to civilization are changes crossing all national boundaries. They are unique in that individuals and nations play a disproportionate part in affecting global change. All of us experience these changes whether or not we are major contributors. The effect on our lives depends on the actions of many. For instance, California's investments to clean up its air are undermined by pollutants carried across the Pacific from thousands of miles away. Local or regional jurisdictions acting alone cannot address a problem of the global commons such as atmospheric change. Yet every day, our local choices in travel, purchases, and use of the built environment, engage a complex material and energy system now dominated by fossil fuels. Our local actions are placed squarely in the commons.

FIGURE 1.1: **City of Aspen Canary Initiative.**

Faced with this dilemma, Aspen created the Canary Initiative. Its success will be, in small part, a measure of its own mitigation, but perhaps more on how it will leverage those actions through other partnerships – from regional initiatives to international efforts in curbing greenhouse gases. It's success will also be a measure of how well Aspen can adapt to change, from ski area strategies, like making snow, to a broadening its economic base and cultural activities in all seasons. While Aspen is subject to whatever course the world takes in reducing greenhouse gases, it can proactively do its part in reducing emissions and in adapting to climate change.

This assessment provides a first look at how global warming could impact Aspen – it's climate, ecosystems and socioeconomic systems with an emphasis on snowpack and skiing. This report is one part of the Canary Initiative. The Initiative includes a rigorous bi-annual greenhouse gas emissions inventory (Heede 2006), an emissions reduction action plan (in draft), and an education and public outreach program that includes conferences, convened by the city, and public awareness campaigns. (Fig 1.1). The primary components of the Canary Initiative were designed to create a set of concrete actions as well as a context for Aspen's response to climate change.

1.1.1 Study area and map

In establishing the study area, the assessment team and the city of Aspen agreed upon the upper Roaring Fork River as a focus rather than the entire Roaring Fork Valley. The area included is the watershed upstream from the confluence of the Roaring Fork River and Woody Creek, including a portion of Pitkin County and all of Aspen (Figure 1.2). The upper bound is the Continental Divide above the headwaters of the Roaring Fork. Although this study does not include the entire Roaring Fork River watershed to Glenwood Springs, many of the climate impacts will ripple through the entire valley. Elected officials and citizens from other communities in the watershed participated in our stakeholder meetings. Eventually the type of work started in this assessment may be carried out in other communities so that a broader picture of impacts, vulnerabilities, and responses can be developed into a more integrated understanding and set of coordinated actions for the valley.

1.1.2 Integrated Assessments

There are several definitions of integrated assessment. Here we consider an environmental assessment as "integrated" when it requires more than one discipline because of its complexity, involves scientists and decision makers, and can offer some insight to the decision making community relevant to their needs, such as how they prioritize resources applied to an environmental problem. The process, as in this case, can involve stakeholders and have a participatory nature. It often involves the development of scenarios and models that are used in exploring the nature of the problem

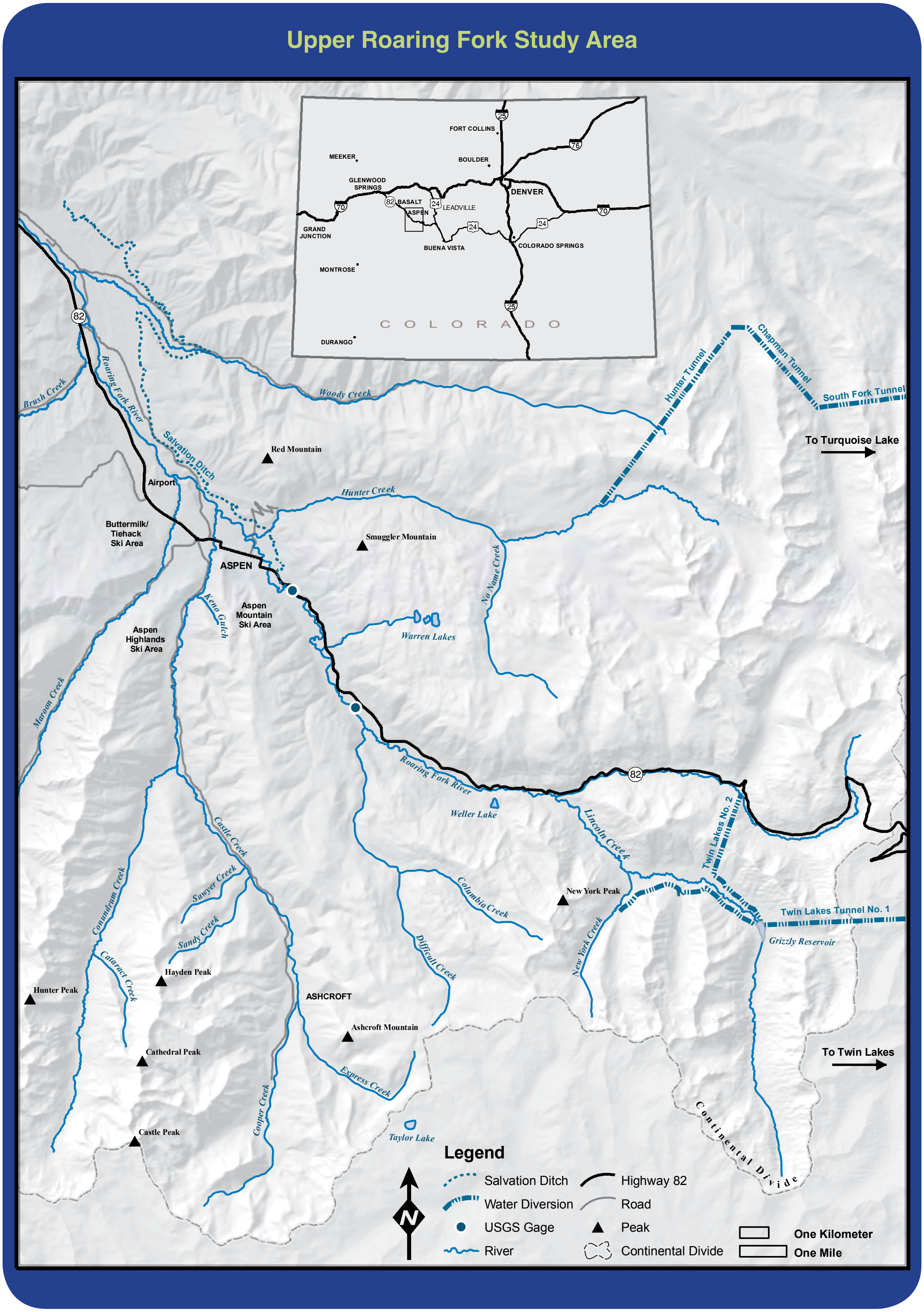


FIGURE 1.2: **Upper Roaring Fork Study Area.** Note the trans-basin diversions via tunnels from the upper Roaring Fork to Twin Lakes and from upper Hunter Creek to Turquoise Lake, both divert water to the eastern slope of the Continental Divide. A major in-basin diversion just up river from Aspen is the Salvation Ditch, which historically supplies irrigation water to ranches on the north side of the Roaring Fork. (Source: Mary Lackner, City of Aspen GIS Department)

and its sensitivity to key factors (Hisschemoller 2001). This assessment is integrated in that it examines aspects of the climate, social and economic systems, and ecosystems. Assessments often raise many questions about the nature of the present complex of systems and how they interact even before exploring possible change in the future.

A key concept in integrated assessments is vulnerability. Given a certain amount of climate change, how vulnerable is a community, both from the extent of climate change itself and the community's ability to cope with that change. The adaptive capacity of a community rests on many factors including infrastructure, monetary and material resource, organizational capacity, and technological options (Patwardhan 2006). Different components of an assessment can be more vulnerable than others and roughly grouped into societal and natural components. For example, Aspen's ability to adapt to altered skier-days and the consequent economic change as compared to the reorganization of plants and animals in response to altered bioclimatic conditions in the Roaring Fork Valley. Many components of the system blur the distinction between nature and society, such as managed flows in rivers, agriculture, and managed lands such as parks.

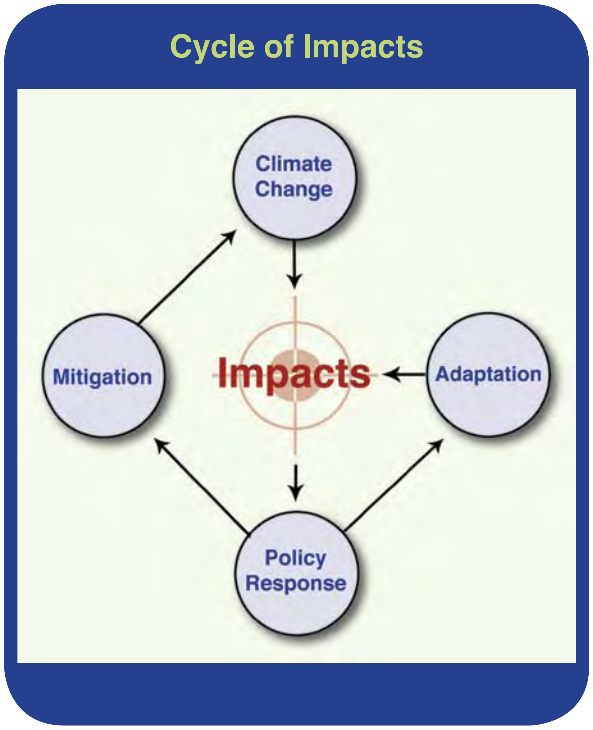


FIGURE 1.3: **Cycle of Impacts.** (Source: Adapted from IPCC, 2000a)

1.1.3 Cycle of Impacts

In an assessment it is useful to consider the parts of a system that produce impacts. Figure 1.3 illustrates the relationships of key components in the cycle of impacts: climate change impacts, policy response, mitigation, and adaptation. As displayed in the figure, climate change causes impacts to the physical environment, such as snowpack, and to socioeconomic and ecological systems. These impacts elicit a policy response. The response can be to mitigate, that is to take action to reduce the cause of climate change by reducing emissions of greenhouse gases. This type of mitigation response reduces the expected climate change, thereby reducing the impacts – a negative feedback dampening the cycle. On the other hand, allowing greenhouse gases to continue to build-up – a policy response of inaction is a positive feedback accelerating climate change and consequent impacts.

Another type of policy response is adaptation. Over the last several decades, ski resorts responded to unreliable snow cover for opening dates by investing in snowmaking equipment. Snowmaking serves as an adaptation, hedging against future climate change. Often the policy response is to mitigate and to adapt. The Canary Initiative's Action Plan (in development-at the time of this publication) will explore a full suite of local mitigations in the context of regional, national and international mitigation strategies. This report focuses on how global warming may affect our regional and local climate, what are some of the important impacts, and explores adaptation needs and strategies raised by stakeholders involved in the assessment, from ranchers to ski mountain managers.

1.2 GLOBAL AND REGIONAL CLIMATE CHANGE

The concentration of greenhouse gases in the atmosphere has increased since the onset of the Industrial Revolution namely because of the burning of fossil fuels, but also due to deforestation and other human activities. As a result, the Earth's climate is changing. There is an international consensus among scientists that there is a measurable change in the Earth's global mean temperature resulting from human activities and to a lesser extent natural phenomena. Substantial progress has been made in projecting these changes decades into the future (as illustrated in the latest report of the Intergovernmental Panel on Climate Change [IPCC, 2001a]) and numerous other studies published since.

Global Climate Change

The climate assessments, reported by the Intergovernmental Panel on Climate Change approximately every 5 years, have arrived at the conclusion that the Earth is warming and much of the warming, particularly since about 1950's due to human activity. Figure 1.4 illustrates the temperature change in the Northern Hemisphere over the last 1,000 years up to the present (red heavy line) and then projects global temperature change for the next 100 years based on different greenhouse gas emissions scenarios listed to the right of the graph. Temperatures in Figure 1.4 are from direct observations from 1860 to the present. Before 1860, Northern Hemispere temperatures are inferred from ice cores, tree rings and other proxy methods. After 2000, the various color lines out to the year 2100 represent the projected temperature with different greenhouse gas emissions scenarios, 3 of which are the scenarios used in this assessment. The projected range of global average temperature for 2100 is from 2.5 to 10.4°F (1.4 to 5.8°C).

Coincident with the rise in the Earth's temperature is an increase in the concentration of carbon dioxide in the atmosphere. Figure 1.5 has the same x-axis (going back 1,000 years) as Figure 1.4 and shows the concentration CO_2 up

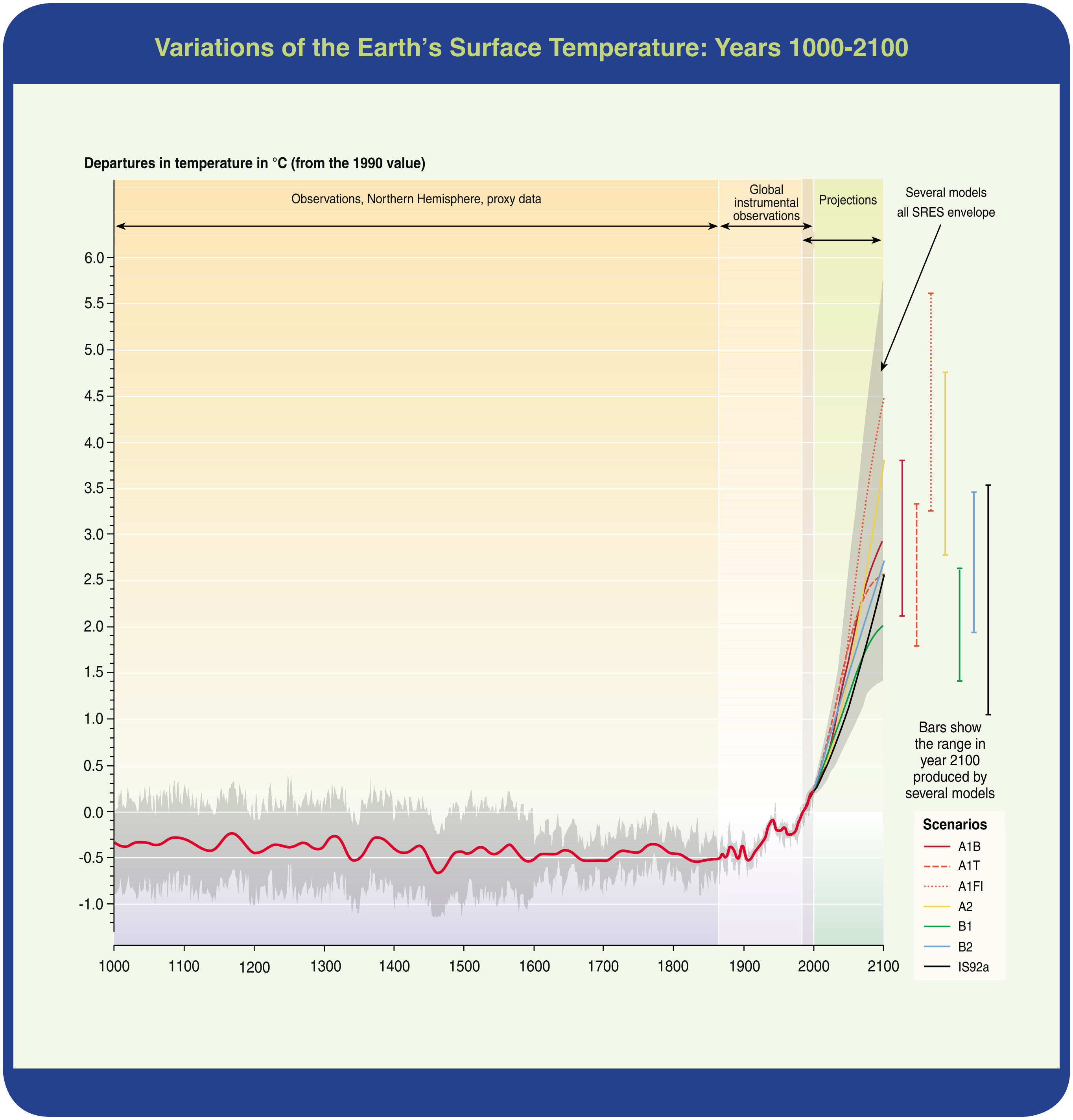


FIGURE 1.4: **Variations of the Earth's surface temperature: years 1000 to 2100.** Over the period 1000 to1860, observations are shown of variations in average surface temperature of the Northern Hemisphere (corresponding data from the Southern Hemisphere not available) constructed from proxy data (tree rings, corals, ice cores, and historical records). The line shows the 50-year average, and the grey region the 95% confidence limit in the annual data. From the years 1860 to 2000, observations are shown of variations of global and annual averaged surface temperature from the instrumental record. The line shows the decadal average. Over the period 2000 to 2100, projections are shown of globally averaged surface temperature for the six illustrative SRES scenarios and IS92a as estimated by a model with average climate sensitivity. The grey region "several models all SRES envelope" shows the range of results from the full range of 35 SRES scenarios in addition to those from a range of models with different climate sensitivities. (Source: Figure 9-1a from the IPCC *Climate Change 2001: Synthesis Report*)

until the Industrial Revolution varied little from 280 parts per million (ppm) for hundreds of years. Additionally, we know from ice cores that this level of CO_2 was fairly constant for thousands of years prior, back to the end of the last ice age. The rapid rise in the Earth's concentration of CO_2, began in the late 1800's as the result of greater amounts of fossil fuel combustion and land use change. After the year 2000, the colored lines are projections of future CO_2 concentrations depending on whether we burn more or less fossil fuel, aerosol emissions and other factors. The emission scenarios in this assessment are listed to the right of the graph as follows: low (B1), medium (A1B), and high (A1FI). These three different emission scenarios result in a range of concentrations by 2100 from about 550 ppm at the low end, using B1, to a little over 700 ppm using A1B, to almost 1,000 ppm using the high scenario, A1FI.

For a given change in GHG concentration it can take the Earth's climate system several hundred years for the climate system to stabilize. The concentration of carbon dioxide that is projected for 2100 will continue to rise into the 22nd century. The resultant temperatures shown in Figure 1.4 also will continue to rise past 2100. These two figures emphasize how low emissions lead to less global warming and how dramatically human activity is altering and will continue to alter the planet unlike any previous time in history.

Figure 1.6 shows the three primary emissions scenarios used in this study, and the projected change in global average temperature they produce over the coarse of the 21st century (MAGCICC/SCNEGEN). Their range plus or minus the mean is the shaded area corresponding to each line. These 3 scenarios are the starting point for the regional analysis in Chapter 2.

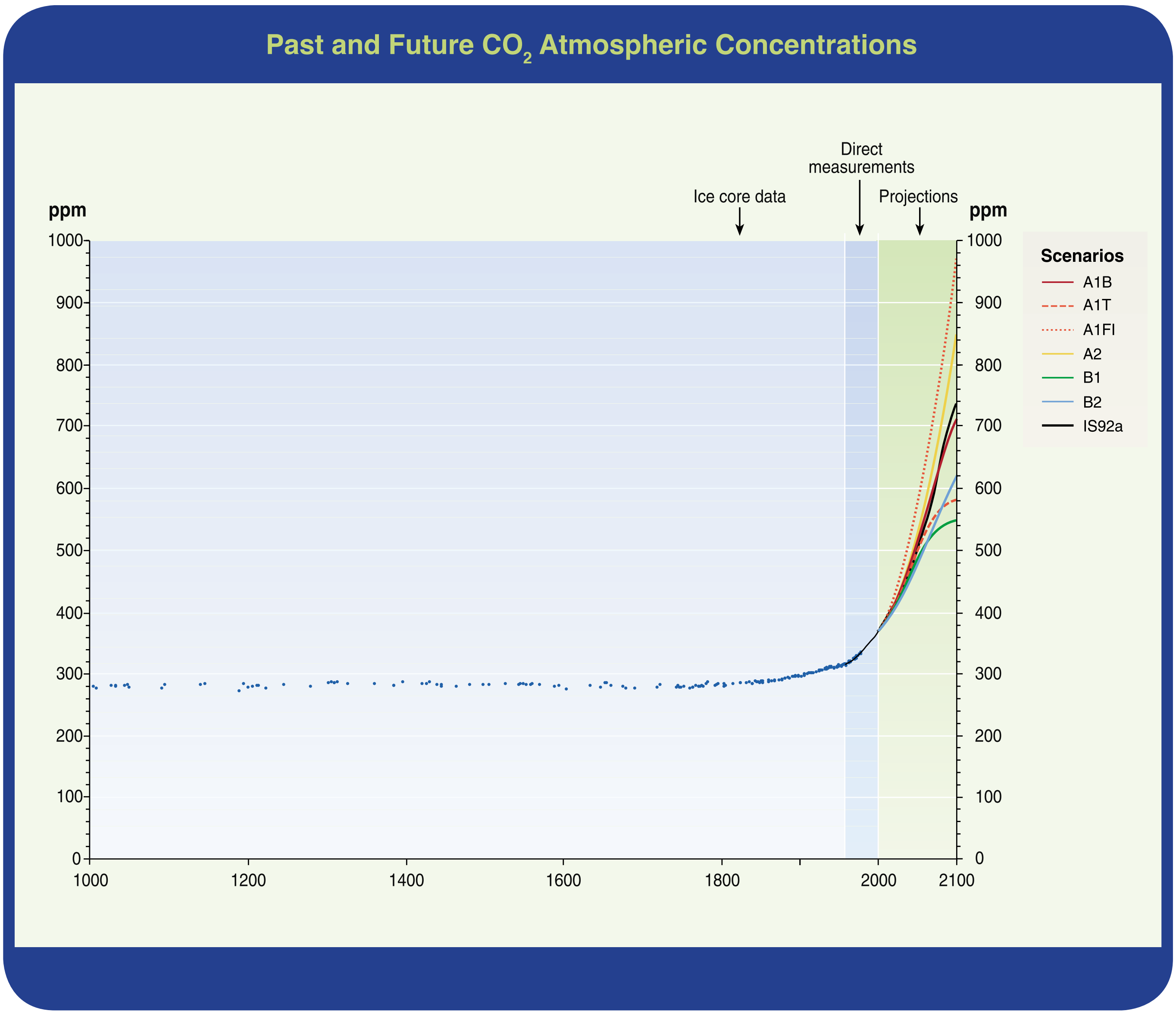


FIGURE 1.5: **Observations of atmospheric CO2 concentration over the years 1000 to 2000 from ice core data supplemented with data from direct atmospheric measurements over the past few decades.** Over the period 2000 to 2100, projections are shown of CO2 concentrations based on the six illustrative SRES scenarios and IS92a (for comparison with the SAR). (Source: Figure 9-1b from the IPCC *Climate Change 2001: Synthesis Report*)

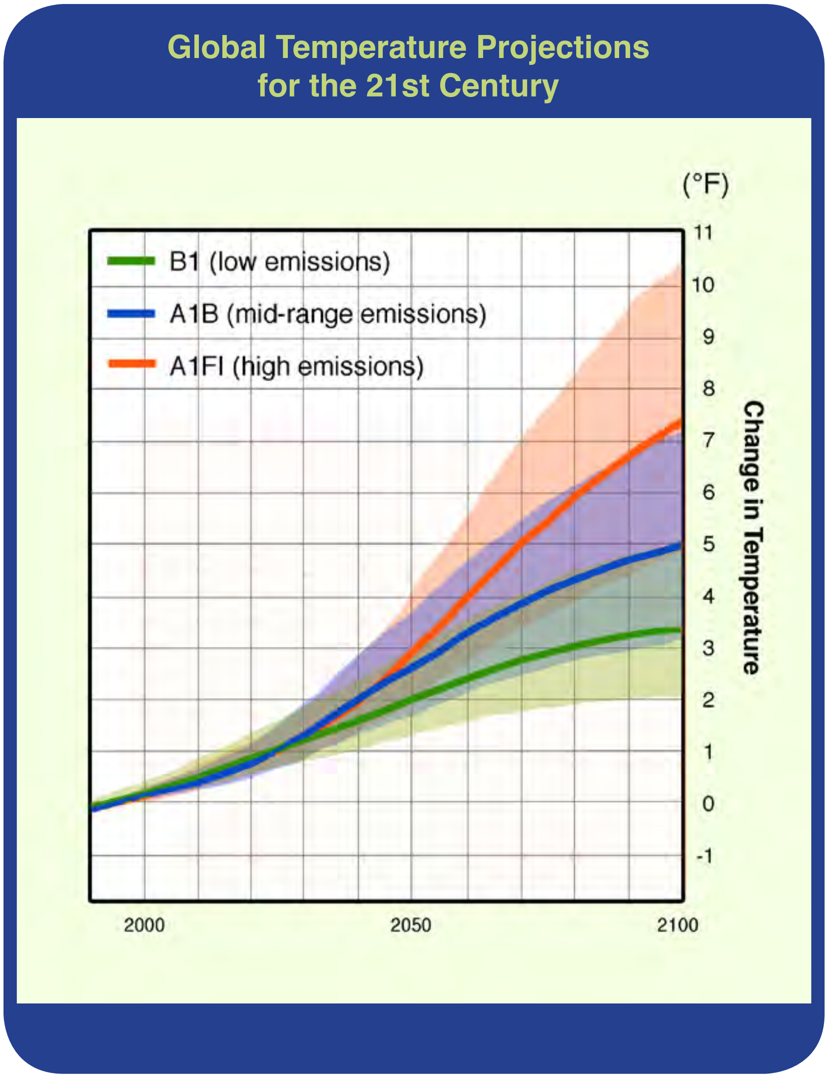


FIGURE 1.6: **Global temperature projections for the 21st century, in degrees Fahrenheit.** Shown are the average and range for three emissions scenarios: B1 (low emissions), A1B (mid-range emissions), and A1FI (high emissions). Data from MAGICC/SCENGEN.

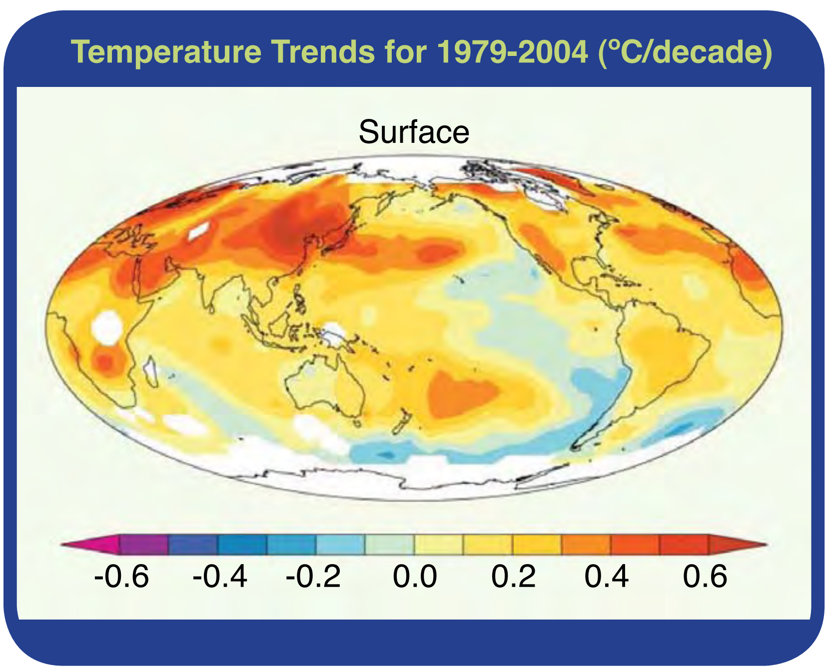


FIGURE 1.7: **Temperature trends for 1979-2004 (°C/decade).** NOAA surface temperature ($T_{S\text{-}NOAA}$). Range of the scale in Fahrenheit is –2.7 to 2.7 °F (–0.6 to 0.6 °C) and use (Source: CCSP, 2006)

Oberved Trends and Regional Climate

Figure 1.4 shows how the global average temperature is projected to change but global averages reveal little of how temperature is distributed around the globe. Figure 1.7 shows temperature trends for 1979-2004 as change in °C per decade. The figure shows what parts of the Earth are warming at different rates. Recent research, corroborating earlier studies of surface temperature trends, shows that the Northern Hemisphere is warming more than the Southern and that mid-continental areas, such as the Rockies, are warming more than coastal areas. Note the orange band over the Western United States. These observed rates of change are rapid compared to the 20th century as a whole and very rapid compared to rates of change since the last ice age.

North America

Figure 1.8 shows new modeling results from the Program for Climate Model Diagnosis and Intercomparison (PCMDI), multi-model experiments conducted at the National Center for Atmospheric Research (NCAR), provided for this study. It indicates that toward the end of the century, assuming a middle emission scenario (A1B), winter warming in North America will be more pronounced in the mountains, and at higher latitudes. For more on North American impacts assessments IPCC, 1998. For an overview of U.S. climate impacts see NAST, 2000.

Rocky Mountains

Mountain environments are especially vulnerable to global warming given the link between temperature and the biotic and abiotic processes that control montane ecosystems (IPCC, 1998; Reiners et al., 2003; Hobbs et al., 2004;). Climate change has long been seen as a potential threat to snowpack and ecosystems in the American West. Gleick (1990) projected that higher temperatures would result in earlier snowmelt and decreased snowpacks in the West. This conclusion has been replicated in many studies such as Miller et al. (2003) and Dettinger et al. (2004). Climate change may also result in major changes in the location and productivity of western ecosystems (e.g., Bachelet et al., 2001). Lenihan et al. (2003) found that the frequency and intensity of fires in the West could dramatically increase as a result of climate change. Changes for the upper Colorado River Basin by mid century are increases in

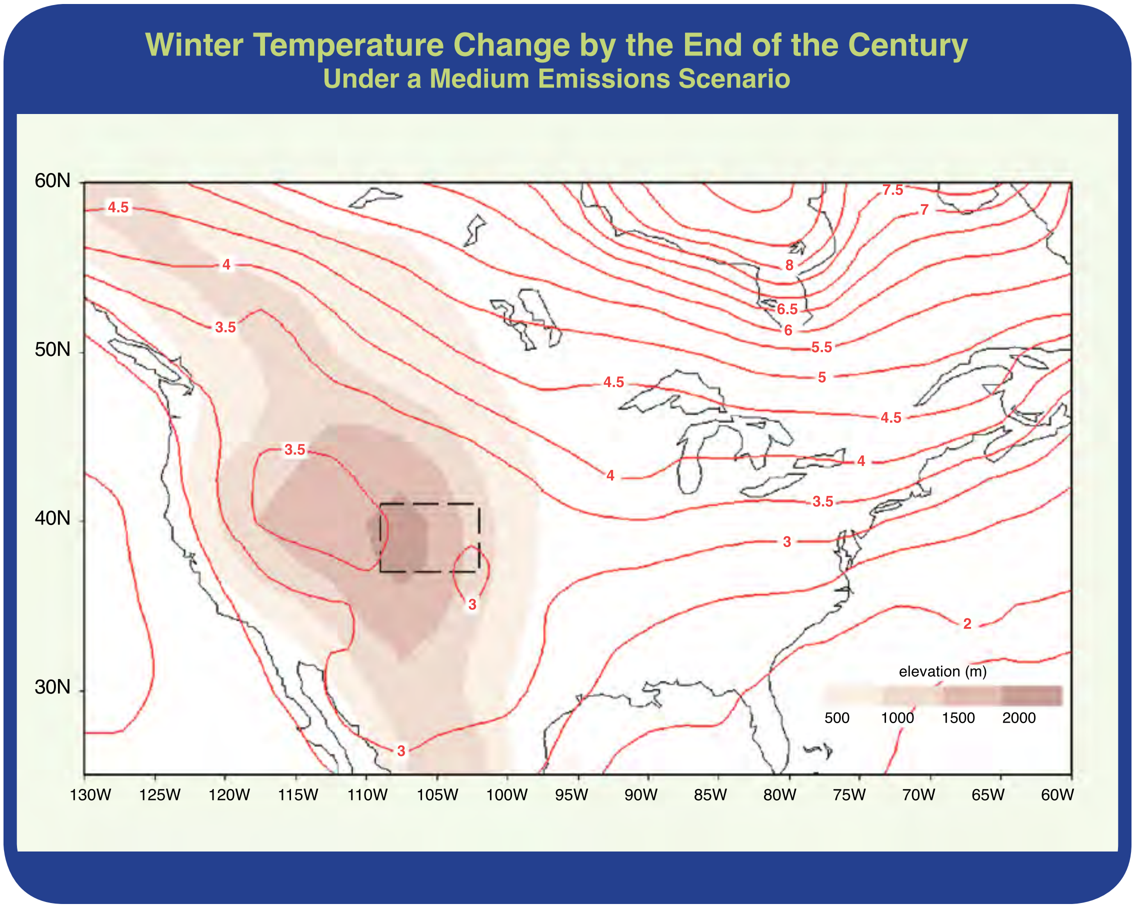


FIGURE 1.8: **Mean December-January-February surface air temperature change (in Celsius) under the middle (A1B) scenario for 2080-2099 relative to 1980-1999.** Averaged in 12 IPCC models. Dashed black box represents Colorado. Brown shading represents elevation and red contour lines are in °C. Range for area shown is1.5 to 9°C, or 2.7 to 16.2°F. Projections show a 3.0-3.5°C, or 5.4-6.3°F increase in temperature for western Colorado. (Source: Plot made for the Aspen project by Haiyan Teng at NCAR utilizing data from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) IPCC Data Archive at Lawerence Livermore National Laboratory. Model data available from: http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php)

temperature and decreases in snowpack, runoff, precipitation, and water storage (Saunders, 2005).

The U.S. Global Change Research Program's regional assessment for the Rocky Mountain/Great Basin area (Wagner, 2003) concluded that higher temperatures would substantially shorten the ski season, as well as add significant costs to ski operations. Reduced skiing would ripple into other dimensions of resorts tied to skiing, such as the second home market. It is reasonable to expect that an increase in temperatures would significantly affect Aspen's ski sector and associated elements of the economy. More precipitation will fall as rain rather than snow, the snowpack is likely to accumulate later in the fall, and snowmelt is likely to begin earlier in the spring. Thus, the ski season will very likely be shortened and lower altitude ski areas and ski runs would be at risk of late openings and earlier closings, and poor conditions in between.

Using the Rocky Mountain/Great Basin regional assessment as a starting point, this assessment began by designing an approach for assessing the impacts of global warming on the Southern/Central Rockies and specifically to the ski industry and its role in Aspen and the Roaring Fork Valley.

1.3 ASSESSMENT DESIGN

Assessment Team and National Advisory Panel

The assessment team consisted of a wide range of expertise including: geography, economics, resort planning, climate modeling, snow and hydrologic modeling, ecology, environmental policy, and decision analysis. The team, assembled by the Aspen Global Change Institute, includes the University of Colorado's Center for the American West, Stratus Consulting Inc., the Rural Planning Institute, and Wildlife and Wetland Solutions, LLC. The team members also worked with scientists from the National Center for Atmospheric Research and the Institute for Arctic and Alpine Research at the University of Colorado.

A National Advisory Panel of distinguished scientists was assembled to guide the assessment by adding experience from international, national, and regional assessments and specific expertise in many disciplines. Members of the national panel participated at three junctures in the assessment process: at the design phase, where the scope and method of the project were being developed, during a mid-process meeting of the assessment team, which included a public lecture, an open house and poster session, the second stakeholder meeting; and finally, in the report review process.

Stakeholder Involvement

Soon after the project was underway, a stakeholder workshop was held in Aspen to review the assessment design, provide an overview of climate change science, and to discuss topics to be included in the study. The stakeholders represented a wide-range of interests including mountain resort businesses (lodging, skiing, consulting, architecture), non-profit environmental organizations, farmers/ranchers, the media, city staff, and political leaders.

A second round of stakeholder meetings was held over two days midway through the assessment process. The assessment team and the national advisory panel met for a one-day technical review of the preliminary findings. That evening, AGCI hosted a well-attended public lecture and an open house poster session. On day two, AGCI reconvened the stakeholders for a presentation of the preliminary findings and discussion of stakeholder priorities.

A third meeting was held with the stakeholders that included an EPA-sponsored streamflow analysis. Nine stakeholders, all of whom were knowledgeable about the Roaring Fork River, were interviewed about climate change impacts to water quantity, quality, runoff, adaptation options, and decision characteristics. The findings of the interviews were then shared with a larger group of stakeholders who contributed to the process through written comments.

1.4 BACKGROUND

1.4.1 Physical setting

In its relatively young tenure as a community, Aspen has already experienced several reincarnations. However, one constant throughout its history is a focus on the outdoors and its natural resources, an important consideration when contemplating the implications of climate change. The physical setting of the Aspen area offers a diversity of landscapes and life zones. The town is located along the Roaring Fork River within a flat and relatively wide part of the upper Roaring Fork Valley. The Elk Mountain Range emerges directly southwest of the town, providing the spectacular surroundings for the four different ski mountains. To the east is the Sawatch Range, with Independence Pass and the Continental Divide. The Colorado Plateau country, with its flat plateaus and wide valleys, unfolds to the northwest, leading out to Colorado's Western Slope.

Aspen's main watercourse, the Roaring Fork River, begins as a trickle near the summit of Independence Pass, and becomes the second largest tributary to the Colorado River in the state by the time it joins the Colorado River in Glenwood Springs. The volume of streamflow generally follows a snowmelt pattern, with flows peaking in late spring to early summer when snowpack melts. Eighty percent of annual moisture is in the form of snow.

The ecosystems surrounding Aspen are determined by topography, aspect, altitude, and latitude – all of which affect temperature, winds, and growing season. In other words, the ecosystems are like microclimates, adapted to very specific moisture amounts, temperature ranges, and topographic orientation. Generally speaking, the landscape can be divided into different life zones which are determined by elevational boundaries and corresponding types of ecosystems. Specific associations of plant and animal species can be found within each life zone. The life zones include:

- Riparian and wetland ecosystems (across all elevations)
- Montane zone, including oak mountain shrublands, sagebrush shrublands, aspen forests, mixed-conifer forest, (7,000 - 9,500 feet [2,130-2,900 m])
- Subalpine zone, made up primarily of spruce-fir forests (9,500 - 11,500 feet [2,900-3,510 m])
- Alpine zone, composed of low shrubs and herbaceous plants, (11,500 feet and above [3,510+ m])

1.4.2 Cultural History

The first known human inhabitants of the area that would later become Aspen were Ute Indians who lived there in the summers to hunt, gather, and fish. They depended on the abundance of wildlife and plants in montane environments like the upper Roaring Fork Valley to support their subsistence lifestyle. They returned to lower river valleys within the Colorado Basin during the winters. Several established Ute summer camps were located in and around present-day Aspen and in nearby tributary valleys such as Conundrum and Castle Creek.

The 1849 California gold rush stimulated prospector activity throughout the western United States including Colorado, activity that eventually trickled into the Aspen area in 1879 with prospectors exploring from Leadville. Discovery of rich lodes of silver resulted in the founding of the city of Aspen in 1881. The town developed at such a pace that optimistic investors facilitated construction of two different hydroelectric plants (one on Hunter Creek, the other on Castle Creek), and a major ore processing facility (Andersen, 2004). In addition, two railroads came to town. In 1893, just as Aspen was bursting with a population over 10,000, the repeal of the Sherman Silver Act collapsed its mining industry. Aspen went from boom to bust practically overnight. The result was an exodus of much of the city's population. This ushered in an agrarian period with a comparatively smaller, but more permanent population (Figure 1.9).

Aspen Station, Colorado Midland Railroad on Durant St. circa 1910. (Photo courtesy of Aspen Historical Society)

Cutting hay on the Gerbaz Ranch, c. 1920. JJ Gerbaz Collection. (Photo courtesy of Aspen Historical Society)

Roch Run, Mill St circa 1937. (Photo courtesy of Aspen Historical Society)

Farmers and ranchers found that they could grow crops like hay, oats, spring wheat, buckwheat, potatoes, and onions on the valley floors. Ranchers grazed cattle on higher elevation range in the summers, wintering them on valley pastures with the summer's hay crop for feed. They responded to the semi-arid climate through the construction of irrigation diversions and a network of ditches that took water from the Roaring Fork River and tributary creeks and carried it to their fields for flood irrigation. The Salvation Ditch, which diverts water from the Roaring Fork River above Aspen to McLain Flats and Woody Creek, was an early irrigation diversion, built in 1903. Another major local irrigation diversion is made up of the upper and lower Red Mountain ditches (from Hunter Creek). Productive cultivation of crops and grazing pasture was impossible without these irrigation diversions, and in fact, before irrigation water came to McLain Flats, it was known as "Poverty Flats."

During these so-called "Quiet Years" after the mining bust, the livelihood of those who stayed in the valley depended on irrigation water and agricultural outputs that it supported. Even now as tourism has come to dominate the upper Roaring Fork Valley's landscape and economy, agricultural land use retains a place, albeit a diminishing one.

Irrigation needs on the drier and more populated east side of the Continental Divide drove the development of many "trans-mountain" diversions, which convey water from one basin to another, usually through tunnels. To tap the upper Roaring Fork basin, the Twin Lakes Canal Company developed such a system in the 1930's to capture water from the upper Roaring Fork River, as well as Lincoln and Lost Man Creeks, and deliver it to agricultural users in the Arkansas Basin. In addition, a part of the Fryingpan-Arkansas Project, built in the 1960's, diverts water from upper Hunter Creek into the Fryingpan Valley, where a major collection system feeds water into the Arkansas Basin via the 10.5 ft (3.2 m) diameter Charles Boustead Tunnel. All of these diversions directly impact flows in the upper Roaring Fork River.

By 1930, Aspen's population had dropped to 700. In an unlikely creative twist, several ski enthusiasts, who wanted to see alpine ski opportunities in the U.S. rival those in Europe, brought the ski development idea to Aspen. The ski pioneers, who included Billy Fiske, Thomas Flynn, and Europeans Andre Roch and Gunther Lange, decided that Mt. Hayden in the Castle Creek Valley was the best north-facing mountain around for a long series of ski runs. They also identified present-day Aspen Mountain's potential for skiing. Roch Run was cut on Aspen Mountain in 1937 and hosted several downhill races.

After World War II, with the help of an enthusiastic and experienced corps of 10th Mountain Division veterans, Aspen's ski culture and business was born.

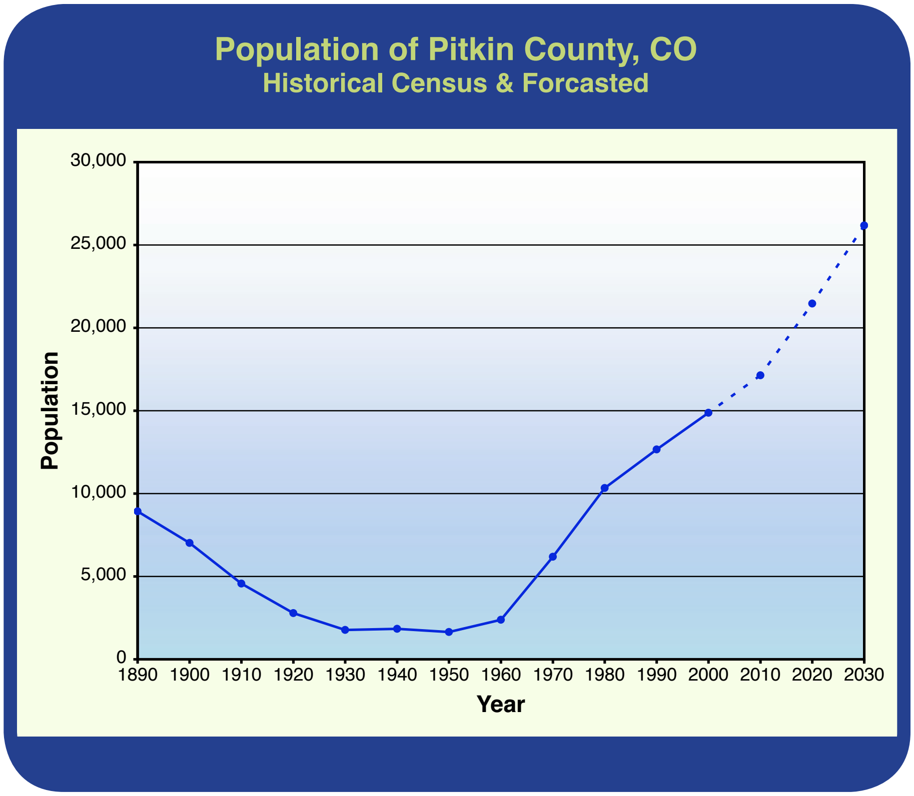


FIGURE 1.9: **Historical census (solid line) and forcasted (dashed line) population of Pitkin County.** (Source: Compiled by the Colorado Demography Section from US Census Bureau Records)

Aspen as a ski resort has grown tremendously since its official opening day in January 1947. Friedl Pfeifer was a key player in the beginning of this new boom. An Austrian-born, 10th Mountain Division veteran and former director of Sun Valley's Ski School, Pfeifer brought the vision for a ski school to Aspen. He garnered the financial support of Walter Paepcke, a Chicago industrialist who became enchanted by the scenic mountain hamlet after his wife Elizabeth visited Aspen in 1939 and raved about it. Paepcke helped form the Aspen Skiing Corporation (now the Aspen Skiing Company), and through the late 1940's and 1950's he and Elizabeth pursued their own vision of making Aspen a cultural center.

The Paepckes' philosophical approach was based on Plato's idea that man could achieve a complete life in a place "where he can earn a living and profit by healthy physical recreation, with facilities at hand for the enjoyment of art, music, and education." Through their stimulus, bringing both financial resources and talented individuals, arose a legacy for Aspen that today rests solidly on institutions formed in the late 1940's including the Aspen Music Festival and School, Aspen Institute for Humanistic Studies, and Aspen's International Design Conference.

Grand Opening of the Aspen Chair Lifts and resort facilities on January 11, 1947. Walter Paepcke; A.E. Robinson, Mayor: and Lee Knous, governor of Colorado. Gov. Knous is making the address. (Photo courtesy of Aspen Historical Society)

As Aspen's summers filled with important intellectual discussions at the Aspen Institute and the brilliant sounds of classical music events, skiing continued to grow to new heights. The additional ski mountains of Buttermilk and Aspen Highlands were developed in the late 1950's and early 1960's. The Snowmass Ski Area, in conjunction with the development of Snowmass Village (known first as "Snowmass-at-Aspen"), came in the late 1960's. In the 1969-1970 season, Buttermilk, Aspen Mountain, and Snowmass tallied 730,500 skier days. Twenty years later, skier days on the three mountains increased 65 percent to over one million skier days.

Several significant changes have taken place within the ski industry over the last 30 years. To help adapt to annual climate fluctuations, small-scale snowmaking activities began at some of Aspen's ski mountains in the late 1970's (Aspen Highlands, Buttermilk), with more comprehensive operations and infrastructure put into place in the 1980's. Snowmaking's purpose is to initiate a base of snow at the beginning of the season, to help assure a Thanksgiving start date. Water for snowmaking comes from various tributaries of the Roaring Fork River. Another major change involved the installation of the Silver Queen Gondola on Aspen Mountain, which opened in 1986. The gondola ushered in a new era for Aspen as a ski resort, bringing new levels of comfort, speed, and access to the mountain.

As a resort, Aspen has grown from its "one trick pony" days as a ski town to a place popular for a wide variety of recreational activities. The sport of golf has grown tremendously, with three golf courses in the Aspen/Snowmass Village area alone. Residents and tourists engage in water-based recreational activities, especially angling, rafting, and kayaking. River outfitters run trips all summer long on the Roaring Fork River, moving to the lower parts of the valley later in summer once upper valley flows decrease. Fly fishing is a vital part of the recreation and tourist economy, with anglers coming from all over the country to fish the renowned Fryingpan and Roaring Fork Rivers. A recent economic study estimated that there are over 34,000 visitor days on the 7.5 miles of publicly accessible river on the lower Fryingpan River, generating $3.7 million in annual total economic output for the Roaring Fork Valley (Crandall, 2002). All of these recreational activities rely on water, in one form or another, and are susceptible to the affects of global warming. Less susceptible is Aspen's counterpart – its cultural scene, which continues to thrive with music and arts festivals and the sophisticated shopping and dining opportunities that rival those of larger cities.

The First Paying Guests at the Highland Bavarian Lodge. Some out of this group would become Aspen's first investors and Ski Corporation officers, 1936. (Photo courtesy of Aspen Historical Society)

1.4.3 Aspen's Vulnerabilities and Strengths

Post-settlement Aspen has positioned its economic livelihood on various approaches of tapping its natural surroundings, whether through mining the mountains' silver, cultivating the seasonally fertile valley floors, creating a well-developed winter playground for ski enthusiasts, or hosting an all-around outdoor beauty for recreational activities. The timing and quantity of snowmelt that provides for spring runoff and summer irrigation availability, and supports flows in scenically and aquatically rich streams and rivers, continues to be one of the strongest patterns of climate in the Roaring Fork Valley. Common to any period in Aspen's history is the emission of greenhouses gases. Sources range from the operation of machinery, sawmills, the silver ore smelter plant, train traffic during the mining days, to the infrastructure support required for ski mountain operations, and the emissions that result from the transportation, commercial businesses and residences. All of these activities have contributed to global warming.

In the future, climate change impacts will emerge and reverberate through many different layers of the upper Roaring Fork Valley, including its economy, recreational habits, natural environment, and beloved landscape. Aspen is fortunate to have a ski industry with four different mountains covering a range of elevations; and to have a diversity of recreational, cultural, and commercial qualities that attract residents and tourists alike. As shown by Aspen's history of resilience, transition, and intellectual pursuits, it has a strong foundation upon which to craft strategies for meaningful communal response to climate change.

1.4.4 Regional View

Water and Climate Change

The theme of water finds its way through Aspen's history, as it does that of the American West. Rights to water are given based on the Prior Appropriation Doctrine, also known by the phrase "first in time, first in right." Those who claimed water first have seniority over others who claimed use to water at a later time. This approach is steeped in the realization that water is a scarce commodity in the arid West. Some years there may be enough water in the stream to satisfy the senior rights and the junior rights. Other years there may be only enough water for the seniors, and in drought years there may not even be enough water for the earliest water right holders.

John Wesley Powell advocated for a "watershed democracy," another idea spawned by the harsh arid West that suggested that planning for human activities should be done at a watershed-level (i.e. not on levels dictated by arbitrary jurisdictional boundaries like we have today, including counties and states). Watersheds represent intact units of snowpack, runoff, and streamflow quantities and patterns, and at the most basic level – water availability. What better way to plan and develop than according to the known water resources at a local/regional level? Powell's advice fell by the wayside and watersheds in the West are compromised by trans-mountain diversions and large water projects. Even so, as climate change unfolds, related changes in watershed hydrology will become vital as they influence and challenge the traditional framework of the Prior Appropriation Doctrine.

Trends in the West

Aspen's recreation-based tourism economy is representative of many mountain resorts that have become attractive to a population with increasingly more leisure time and an appreciation for mountain scenery and related recreation opportunities. In contrast to a Western landscape that was once defined by land-based uses including extractive industries and agriculture, the "New West" (Riebsame, 1997) is a place characterized more by urban influences. It is fueled by technological change (e.g. telecommuting), retiring baby boomers (second homeowners), a demand among residents and tourists for cultural and urban amenities, and an outdoor recreation craze that includes everything from golf to mountain climbing to hiking to snowboarding. Adapting to climate change in the New West involves finding strategies to curb carbon emissions and effectively plan ahead for constraints on natural resources (such as water) arising from current population growth trends.

(Photo Credit: Zach Ornitz / Aspen Daily News

Recently, with the combination of dramatic population increases in the western U.S. and occurrence of drought, there is a greater awareness of water quantity and quality issues. Competition for the Colorado River's water is intense, especially as growing metropolitan areas seek additional water, and in so doing, butt heads with age-old agricultural demands and newly emerging environmental and recreation interests. In response to the 2002 drought, which depleted streams, created conditions that led to major wildfires, and forced water conservation in many communities, Colorado has embarked on a statewide water planning process known as the "Statewide Water Supply Initiative (SWSI)," an effort that will culminate in late 2006. Through the many roundtable meetings, stakeholders representing various interests have sought balanced solutions to provide for the state's anticipated water needs in 2030 (which exceed projected availability). SWSI uses state demographer population projections to estimate water needs. Climate change was mentioned in the initiative as one of several types of uncertainties that can either increase or decrease future water availability. The state is also facilitating a process for inter-basin compact negotiations, attempting to forge proactive water use agreements between different geographic areas and interest groups that have traditionally been locked in conflict over water allocations.

At a more local level, several planning efforts have been sparked by water resource issues in the Roaring Fork Watershed. The Roaring Fork/Fryingpan Multi-objective Study (BRW, et al. 1999) addressed flooding impacts and mitigation approaches after a 60-year flood event struck the Basalt area in 1995. And presently, the Watershed Collaborative, a group of valley-wide interests are engaged in efforts to identify water quality and quantity issues in the Roaring Fork Watershed. The group's mission is to assist individuals, organizations, and local, state and federal agencies in the effective planning and management of land and water uses within the Roaring Fork Watershed (http://www.roaringfork.org/sitepages/pid169.php). Implications of global warming will be incorporated into the watershed plan

Summary

Aspen, along with other mountain resort communities, is poised on the brink of a century or more of major climate change. The mining boom-bust cycle Aspen experienced in the past had lessons to offer a struggling community and it emerged after WWII with new diversity and vigor. Many of the anticipated impacts from climate change will be witnessed earlier in the mountains, just as they are evident at higher latitudes. How much warming Aspen will experience is ultimately up to humanity. Diversity has been a key to the success and resiliency of Aspen in the past and may well serve it in the future. Adaptation to climate change will be fundamental in reducing Aspen's vulnerability. Understanding the nature of climate change and how it may affect our region is a principal component of small mountain communities, such as Aspen, in devising meaningful strategies for mitigation and adaptation. This report is a step in providing that basis of understanding.

2. PAST & FUTURE CHANGES IN ASPEN'S CLIMATE

2.1 INTRODUCTION

This section of the report discusses recent trends in Aspen's climate, the selection of climate scenarios, the various modeling approaches used, and the results of the scenarios. The capability to model the climate at regional or sub-regional scales is an emerging science. Obtaining useful information at small scales such as Aspen and the Roaring Fork Valley is compromised by present-day computing capability and knowledge of the climate system. Colorado's mountains add an additional layer of complexity. Given the uncertainties and scale issues discussed, the general approach here is to explore climate change for the region and the Aspen area from a multiple set of assessment techniques. These include the selection of high, medium, and low emissions scenarios, climate sensitivities, and various climate model approaches from large-scale grid box output for the region to higher resolution regional climate models and statistical downscaling techniques.

This strategy was adopted given the limitations of any one technique and the resources available to the assessment team. The core of the analysis is based on the results from a program developed for the purpose of impact assessment analysis, MAGICC/SCENGEN (Model for the Assessment of Greenhouse-gas Induced Climate Change / SCENario GENerator). We used MAGICC/SCENGEN because it has the flexibility to easily alter input parameters such as the choice of standard IPCC emissions scenarios, climate sensitivity, individual GCMs. study area, and other factors such as aerosols. In general there is convergence regarding change in temperature from the various modeling approaches used in this assessment, with less confidence in modeling results for precipitation. This chapter reviews recent changes in Aspen's climate and uses scenarios to show how increased GHG concentrations could change Aspen's climate in the 21st century.

In the last 25 years, Aspen became warmer by about 3°F and drier. Snowfall decreased 16%.

2.2 RECENT CLIMATE TRENDS

Overview

As discussed below, Aspen's climate has been changing in recent decades and is likely to substantially change in the future because of increased greenhouse gas (GHG) concentrations in the atmosphere. Temperatures are likely to rise, precipitation will change, as will variability. How precipitation and variability will change is uncertain. How much temperatures will warm is more certain. In addition, the intensity of precipitation of events could increase.

In the last 25 years, Aspen became warmer by about 3°F (1.7°C) and drier – total precipitation decreased about 6%. The amount falling as snow has decreased by 16%. Higher in the area mountains, at the 10,600 ft (3,231 m) Independence Pass SNOTEL weather station, total precipitation decreased 17% in the last 25 years.

Temperature

Figure 2.1 displays average annual high and low temperatures in the city of Aspen since 1949. The Aspen weather station was moved at the end of 1979 to a site 203 ft (62.9 m) higher in elevation and 0.6 miles (1 km) in distance from the previous site (its current elevation is 8,163 ft [2,488 m]). The 30 year period from 1949 to 1979 shows a slight increase of 0.3°F (0.2°C) in annual average temperature. The average maximum (daily high) temperature during this period decreased (at a rate of –0.6°F per decade [0.3°C]) while the average minimum (nighttime) temperature increased 0.7°F per decade (0.4°C). Since 1980, maximum temperatures have increased at a rate of 1.5°F per decade (0.8°C) and minimum temperatures have increased at a rate of 1°F per decade (0.6°C).

Frost-Free Days

The number of frost-free days recorded at the Aspen weather station in the last 25 years has increased substantially by 20 days. Figure 2.2 displays the change in the number of frost-free days over the second half of the 20th century. The fluctuations in the figure represent high interannual variability. The number of frost-free days on Aspen Mountain will be lower than at the base of the mountain because of the higher elevation, but a similar downward trend in frost-free days is likely.

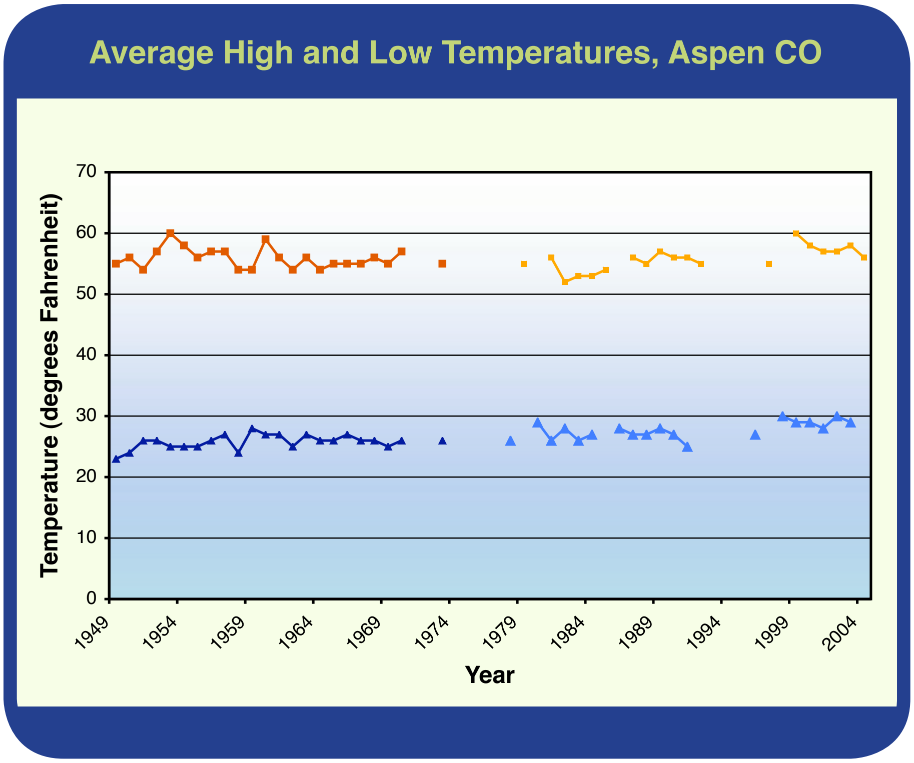


FIGURE 2.1: **High and low temperatures in Aspen as recorded at the Aspen National Weather Service Cooperative Network Station, 1949-2004.** Years with months missing 26 or more days of data are not shown. (Note: The Aspen weather station was moved in 1980 from an in-town elevation of approximately 7945 feet to 8163 feet at the Aspen Water Treatment Plant. Dark blue and orange points represent data from the old Aspen station. Light blue and orange points represent data from the current Aspen 1 SW station.)

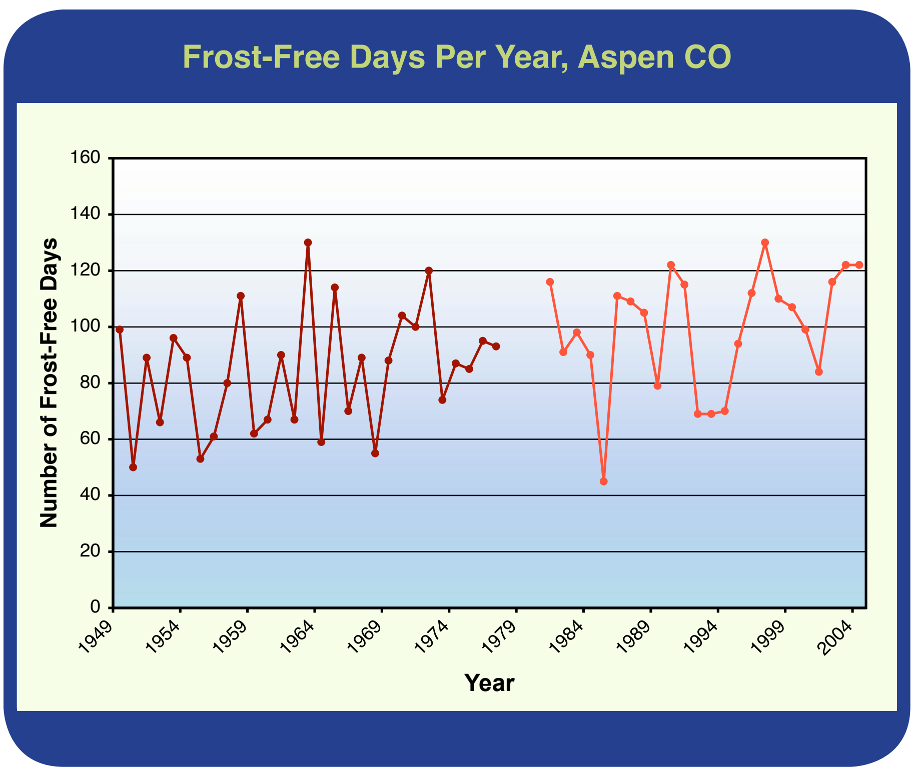


FIGURE 2.2: **Frost-free days per year in Aspen as recorded at the Aspen National Weather Service Co-operative Network Station, 1949-2004.** (Note: The Aspen weather station was moved in 1980 from an in-town elevation of approximately 7945 feet to 8163 feet at the Aspen Water Treatment Plant. Dark red represents data from the old Aspen station. Light red represents data from the current Aspen 1 SW station.)

Total Precipitation

Figure 2.3 displays annual precipitation in town. Total annual precipitation increased from 1949 through 1979 (at a rate of 2.7 inches per decade [6.9 cm]), and has decreased slightly (–0.6 inches per decade [–0.4 cm]) in the 25 years since the station move. The 25 year average annual precipitation in town is 24.2 inches (61.5 cm). At the Independence Pass SNOTEL site, the average annual precipitation (30.8 inches [78.2 cm]) is greater than in Aspen, as is typical for higher elevation stations. Analysis in Chapter 3 shows that ski-season precipitation at the SNOTEL site is very likely to be similar to the conditions on top of Aspen Mountain.

Snowfall

As total precipitation has decreased in the last 25 years, so has snowfall. Figure 2.4 displays annual snowfall amounts in Aspen. Snowfall in Aspen has decreased at a rate of –12 inches per decade (–30.5 cm) over the last 25 years. In contrast 1949 to 1979 showed an upward trend of 15 inches per decade (38.1 cm). The data can also be interpreted to indicate an oscillating (regularly rising and falling) trend. The average annual snowfall for Aspen over the last 25 years has been 173 inches (439 cm).

2.3 EMISSIONS AND CLIMATE CHANGE SCENARIOS

This section looks at what may lie ahead for Aspen's climate as a result of increased GHG emissions. While some aspects of change, such as projections of increased temperature, are virtually certain, other aspects, such as whether seasonal precipitation will increase or decrease, are more uncertain and still encompass a wide range of possibilities. In examining the implications of Aspen's climate change on snowpack and ecosystems, it is important to capture what is known and not known about the change in climate.

Scenarios are plausible combinations of

conditions that can represent possible future situations and can be used to examine how systems can respond to such change in conditions. For example, businesses might use scenarios of future economic conditions to decide whether some business strategies or investments make sense now. Ideally, scenarios should reflect a reasonable range of potential change in climate. That way, uncertainties about changes in key variables such as precipitation, can be captured across the range of scenarios.

Climate change scenarios are developed because predictions of climate change at the regional scale have a high degree of uncertainty. Although it is highly likely that temperatures will eventually rise in most regions of the world,[3] the regional and seasonal details of these changes are only beginning to be understood. Even where the direction of change is certain or likely, there can be uncertainty about the magnitude and path of the change. *We create scenarios as tools to help us understand how regional climates may change so as to understand how sensitive systems may be affected by various possible changes in the climate.*

2.3.1 Time Period

The main group of scenarios developed for this study utilize two time periods: 2030 and 2100. Projections for 2030 and 2100 are not to be interpreted as what will happen in a particular year, but rather what the models indicate will happen within a range of years centered on 2030 or 2100. Some of the other models used in the assessment express the same notion as a range of years, such as 2080 to 2100. These time periods are selected to provide an indication of how average climate conditions may change in the decades ahead. We have chosen these time periods because 2030 is roughly a generation ahead, and within the "foreseeable future" and planning horizons for some stakeholders, while 2100 is intended to capture long-term climate change by the end of the century. It is important to note that most of the

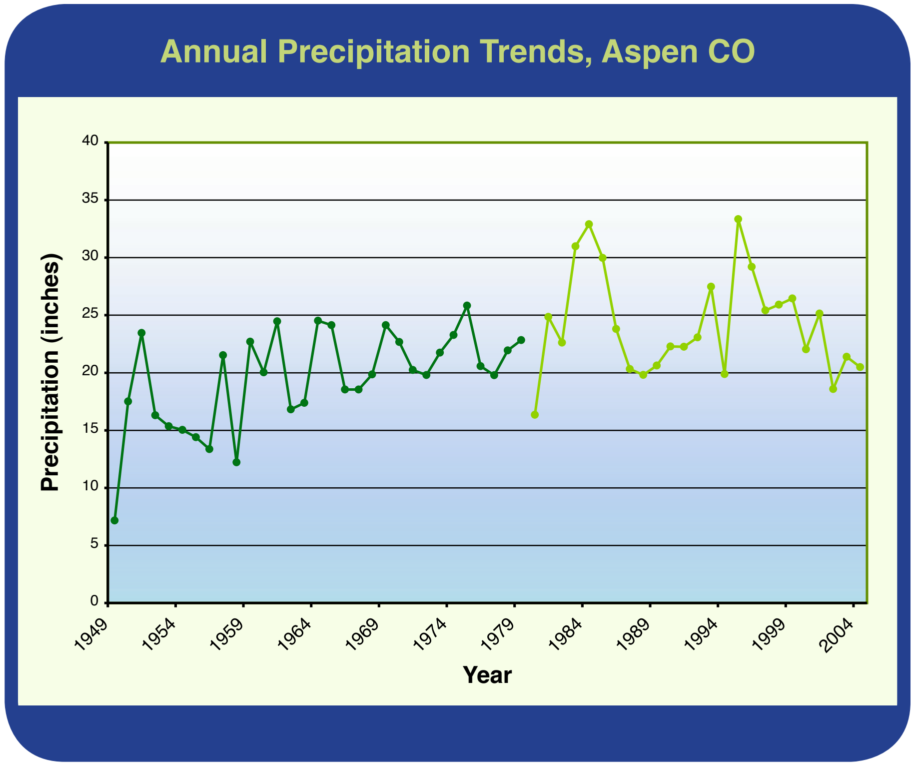


FIGURE 2.3: **Annual precipitation as measured at the Aspen National Weather Service Cooperative Network Station, 1949-2004.** (Note: The Aspen weather station was moved in 1980 from an in-town elevation of approximately 7945 feet to 8163 feet at the Aspen Water Treament Plant. Dark green represents data from the old Aspen station. Light green represents data from the current Aspen 1 SW station.)

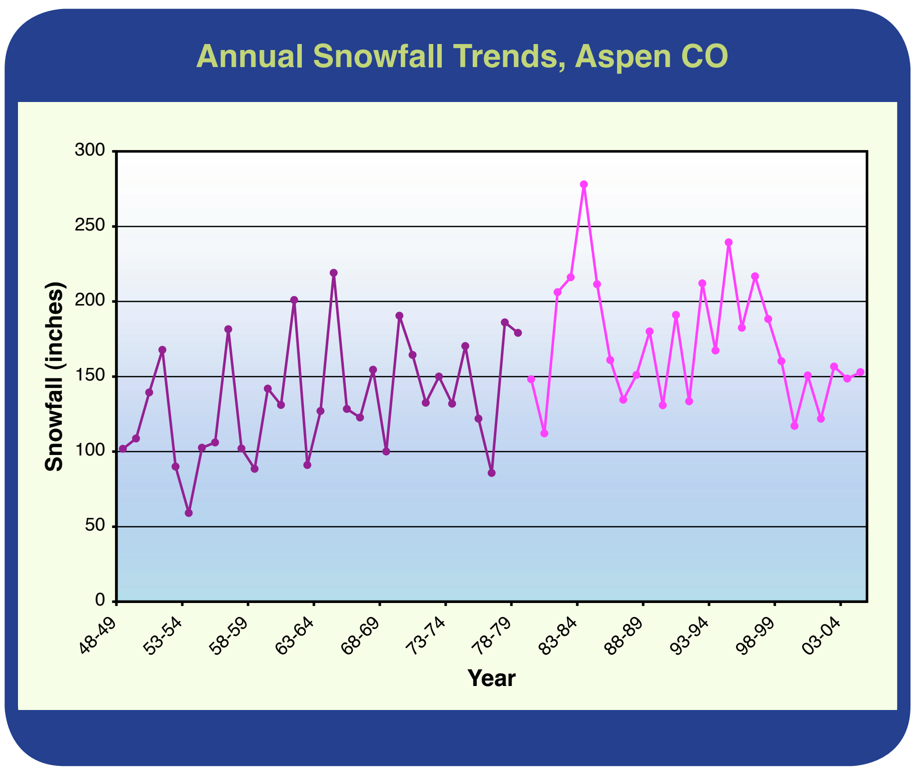


FIGURE 2.4: **Annual snowfall as measured at the Aspen National Weather Service Cooperative Network Station, 1948/49 - 2004/05.** (Note: The Aspen weather station was moved in 1980 from an in-town elevation of approximately 7945 feet to 8163 feet at the Aspen Water Treatment Plant. Dark purple represents data from the old Aspen station. Light purple represents data from the current Aspen 1 SW station.)

3. Other anthropogenic activities such as land use change and air pollutant emissions can have significant effects on local and regional climate change relative to the influence of increased GHG concentrations.

Global Climate in the 21st Century

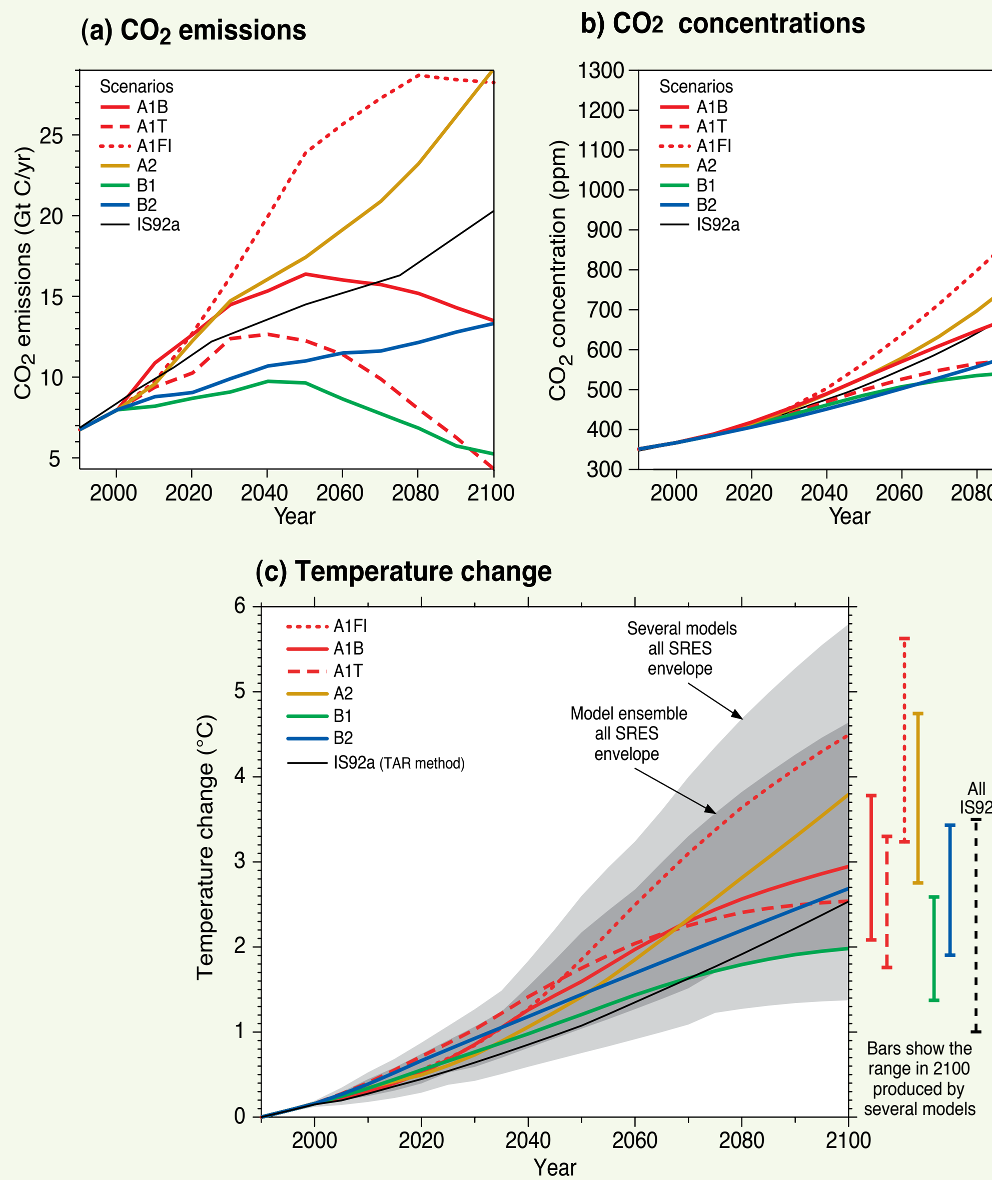


FIGURE 2.5: **Projections of CO2 emissions, CO2 concentrations, and temperature for the 21st Century from the Intergovernmental Panel on Climate Change (IPCC)** ***Special Report on Emissions Scenarios*** **(SRES).** Temperature scale ranges from 0-6ºC, or 0-10.8ºF. The three emission scenarios predominantly used in the Aspen study are A1FI (fossil-fuel intensive; high emissions), A1B (balanced energy; medium emissions) and B1 (environmental emphasis; low emissions). (Source: Figure 5 from Summary for Policy Makers in IPCC, 2001a)

emissions scenarios described in this study do not result in a stable change in climate by 2100, but rather continue forcing change in the climate system well after 2100.

2.3.2 Key Scenario Components

Three factors are critical for determining how Aspen's climate can change, each representing a unique set of issues and inserting levels of uncertainty:

1. GHG emissions: The nature and intensity of human activities, particularly the emission of greenhouse gases from the combustion of fossil fuels and aerosols.

2. Sensitivity of global climate: How much and how rapidly the global climate will respond to increases in GHG concentrations and other human influences.

3. Pattern of regional climate change: How changes in the global climate will affect the climate of Aspen/ Roaring Fork Valley, the southern/central Rocky Mountains, and the western United States. Each of these is discussed in more detail in the following section.

Global Greenhouse Gas Emissions

Future changes in GHG emissions depend on many factors, including population growth, economic growth, technological development, policies, and society's use of energy. The Intergovernmental Panel on Climate Change (IPCC) tried to capture a wide range of possibilities in its *Special Report on Emissions scenarios* (IPCC, 2000a). Their scenarios reflect a wide range of estimates for population growth, economic growth, the level of economic integration, the strength of environmentalism, and improvements in technology (Appendix A briefly describes the A1 and B1 scenarios).

Scenarios reflect a wide range of estimates for population growth, economic growth, the level of economic integration, the strength of environmentalism, and improvements in technology.

The scenarios result in a wide range of emissions and atmospheric concentrations of GHGs. Since likelihoods are not given for these scenarios, we decided to use a range of them to reflect a wide range of potential future GHG concentrations. The A1B scenario ends up close to the middle of the IPCC Third Assessment Report (TAR) range of temperature warming by 2100 (IPCC., 2001a). However, A1B has very high sulfur dioxide (SO_2) emissions early in the century. Since sulfate emissions can result in decreased precipitation in the Rockies (Borys et al., 2003), this scenario would have a substantial impact on precipitation over the Rockies. Nonetheless, A1B serves as the middle scenario because it is in the middle range of GHG emissions and is also in the middle of the range of CO_2 concentrations by the end of the century.

At the high-end of emissions, A1FI has the highest CO_2 concentrations by the 2090s. Since A1FI yields the greatest increase in global mean temperature (GMT) by the 2090s, we will use it as the high emissions scenario. B1 has the lowest GMT warming by the end of the century. Consistent with our reasoning for using A1FI as the high emissions scenario, we will use B1 as the low emissions scenario since it has the lowest increase in GMT. These two scenarios present a stark and interesting contrast between development paths. Although nothing explicit has been said, it would be reasonable to conclude that in its "Canary Action Plan," the City of Aspen wishes to not only reduce its own emissions, but to influence other municipalities around the world to develop programs to set emissions levels at or lower than the B1 IPCC scenario.

Figure 2.5(a) displays the projected carbon dioxide (CO_2) emissions for each of these scenarios (and a few others). Compared to current global emissions of 7 gigatons of carbon per year (GtC/yr), the A1B scenario reaches 15 GtC/year by 2030, peaking at about 17 GtC/year by 2050, and declining to about 13 GtC/year by 2100. The A1FI scenario has slightly higher CO_2 emissions than A1B by 2030, but by 2050 is at 24 GtC/year, and by 2080 reaches 29 GtC/year. From there, the emissions slightly decrease. In contrast, the B1 scenario has emissions of 9 GtC by 2030, peaks at 10 GtC in 2040, and then declines to about 6 GtC in 2100 – the "greenest" of the main IPCC scenarios.

Figure 2.5(b) displays the CO_2 concentrations that would result from these emissions scenarios (as estimated by the IPCC). Note that the CO_2 concentration was around 280 ppm (parts per million) before the Industrial Revolution and had been at that approximate level for five to ten thousand years. Since then, the concentration has increased to about 380 ppm. If the emissions follow the A1B scenario, which represents the mid-range of projected future emissions, the CO_2 concentration is close to 700 ppm by 2100 – 2.5 times the pre-industrial level. A1FI has the highest concentrations, reaching over 900 ppm by 2100 and B1 has the lowest, reaching just above 500 ppm by 2100. Its important to note the range of temperature change for the global world average as displayed in Figure 2.5(c) depicts a range above and below the main line drawn for each scenario – from the lowest to the highest of approximately 4.5 to 18.9° (2.5 to 10.5°C). Generally temperatures in mid-latitude and mid-continental areas such as Colorado are expected to increase more than the global average (IPCC, 2001a).

In Figure 2.5(b) by 2030 there is very little difference in global CO_2 concentrations across the SRES scenarios, although there are already substantial differences in CO_2 emissions (Fig 2.5(a)) and differences in the increase in global mean temperature (Fig 5(c)). There are, however, substantial differences in aerosol emissions that can have significant impacts on regional climate. By the 2090's, there are major variations in CO_2 concentrations and SO_2 concentrations across the SRES scenarios. Since there is little difference in CO_2 concentrations in 2030, we will only use the middle SRES scenario (A1B) for 2030, which will also serve as a middle scenario for 2100.

Two key aspects of the SRES scenarios are that they do not define all possibilities nor do they include policy intervention by nation-states. Aggressive intervention and technological change could conceivably put the world on a path of lower emissions than the IPCC low scenario B1.

Sensitivity of Global Climate to GHG Changes

The second critical factor affecting climate change in Aspen is how much the Earth's climate will warm for a given change in the atmospheric concentration of CO_2. Typically, the sensitivity is expressed as how much global mean temperatures will eventually rise as a result of doubling atmospheric CO_2 concentrations ($2 \times CO_2$). Estimates of this quantity have been derived from a number of sources, including theoretical analysis of system behavior, use of analogues of climate changes in the geological past, and by determining the best fit to changes in the climate over one or more centuries into the past. These studies suggest that, once the global climate has had an opportunity to equilibrate to the higher CO_2 concentration, a doubling of the concentration will lead to a global warming of about 5.4 ± 2.7°F (3 ± 1.5°C). The main reason for this range is uncertainty about how clouds and other critical factors will respond and adjust. Based on a recent review of estimates of the climate sensitivity (reported on by Kerr, 2004) and on consultations with atmospheric scientists on our advisory panel, the assessment team decided to use the traditional range of estimates as the most appropriate way to consider impact analyses; thus, we considered 5.4°F (3°C) as

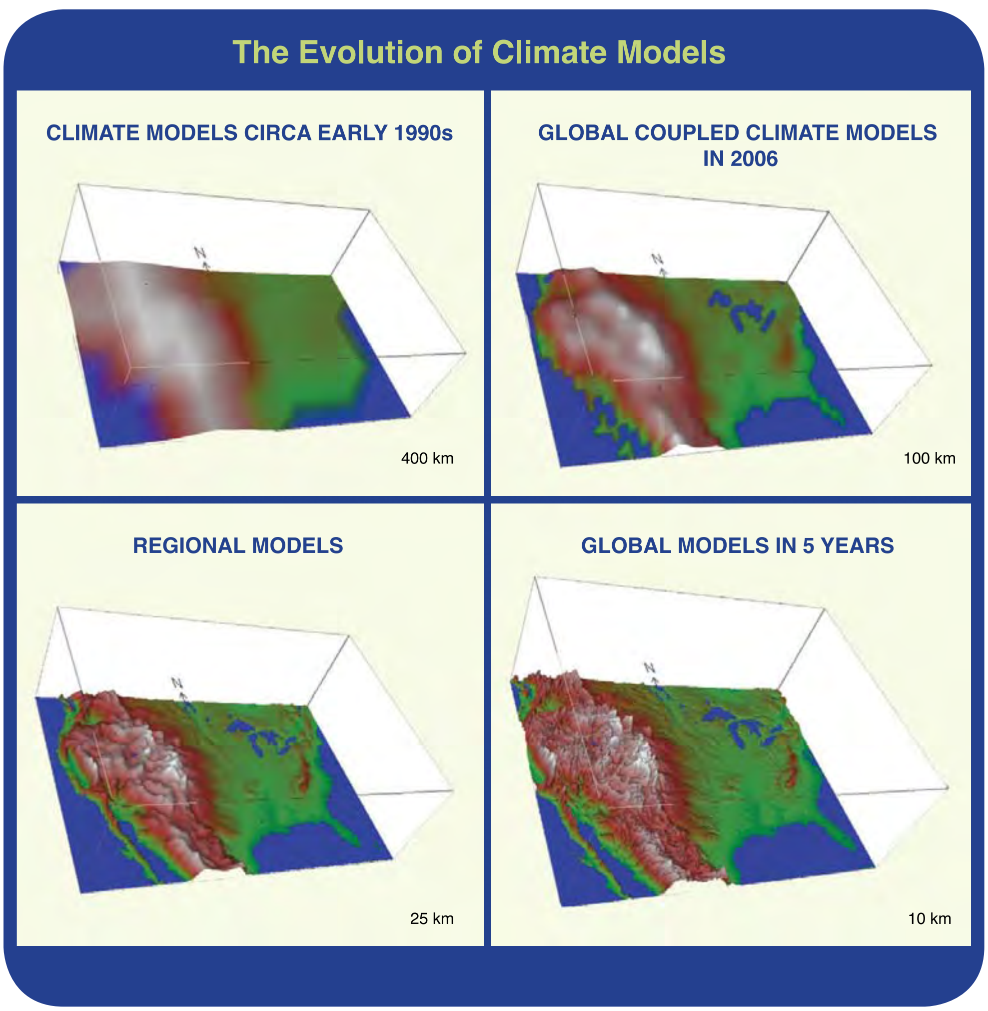


FIGURE 2.6: **The evolution of the resolution ability of climate models.** (Source: Gerald Meehl, NCAR)

the central estimate of the climate sensitivity, 8.1°F (4.5°C) as the high end of sensitivity, and 2.7°F (1.5°C) as the low end of sensitivity.[4]

Regional Patterns of Change

The third source of uncertainty will address how regional climate will change as GHG concentrations increase. This includes how much temperatures in the Southern/Central Rockies will increase relative to increases in global average temperature, as well as how the amount and timing of precipitation in the region will change. As illustrated in Figure 2.6, the ability of general circulation models (GCMs) to represent mountains by having higher grid box resolution is improving. This, in combination with faster computing speed and better understanding of interactive Earth system processes, holds promise that future models will be able to do a better job of representing likely climate change at smaller scales.

Parallel to the improvement in GCMs has been the evolution of downscaling techniques to model climate at the regional and sub-regional scales. There are two primary methods: the first is to imbed a dynamic model within the grid scale of a GCM – these models are known as Regional Climate Models (RCM); the other method is to statistically downscale from GCM grid scale to sub-grid scale. Both of these downscaling techniques are represented in the model selection for this study.

Climate modeling for Colorado presents some additional challenges as mentioned in Chapter 1. Beyond its mountainous topography, there are several major air mass movements affecting the region. How they will change in the future is uncertain. Colorado is influenced by moisture laden storm tracks from the Pacific, drier storm tracks from the north, and dry or wet storm tracks from the south (Benedict 1991, Baron 2002). How these systems enter Colorado, either on the west or east side of the Continental Divide, has a major influence on precipitation patterns for the Roaring Fork Valley and Aspen. For example, it is not uncommon for the San Juan Mountains to the south to receive good snowfall while Aspen receives little and vice-versa. However, the ability of GCMs to represent major atmospheric circulation patterns is improving, as is the ability to represent telekinections to distant phenomena with local regional effect, like El Nino.

2.4 MODEL SELECTION AND APPROACH

The study team used four approaches for generating climate change scenarios for this region (the scale of the grid boxes for these modeling approaches (as well as for the vegetation modeling utilized in Chapter 4) is represented in Figure 2.7). The first is the "MAGICC/SCENGEN tool," which is described below (Wigley, 2004). It can be used to examine the degree to which models agree about projections of temperature and precipitation change given emissions scenarios and climate sensitivities. As noted, MAGICC/SCENGEN will provide climate change estimates over a very large area.

To get higher resolution estimates of changes in climate in the Aspen area, three additional approaches were utilized. The first of these is the dynamical downscaling output from a regional climate model (RCM). RCMs are high-resolution climate models that are built for a region, e.g., the United States, and are "nested" within a general circulation model (in this case the Parallel Climate Model, PCM). This model run is referred to as the PCM RCM.

> There are models that do some things better than others, but no one model that does everything better.

The second high-resolution approach is called statistical downscaling. It uses the statistical relationship between variables in a GCM and observed climate at a specific location such as a weather station to estimate how climate at that specific location may change. This approach is referred to as SDSM (Statistical Downscaling Model).

The third approach is a multimodel or ensemble approach utilizing the current generation of Program for Climate Model Diagnosis and Intercomparison (PCMDI) GCMs[5] combined with a Bayesian statistical model to synthesize the model output information into a set of probability distribution functions (PDFs) of temperature and precipitation change. This model run is referred to here as PCMDI GCMs.

4. Kerr (2004) notes that there is confidence among climate modelers that the 2 × CO_2 sensitivity is not below 1.5°C (2.7°F). The most likely sensitivity is between 2.5°C and 3°C (4.5 and 5.4°F). Kerr reports that the most probabilistic sensitivity is 3°C. There is substantial uncertainty about the upper end of the range. A number of studies such as Forest et al. (2002) and Andronova and Schlesinger (2001) find that there is a 10% chance the upper end of the range is as high as 7 to 9°C (12.6 to 16.2°F) for a doubling of CO_2.

5. The generation of GCMs utilized by Tebaldi et al from PCMDI are similar to models utilized in the IPCC Fourth Assessment Report (AR4), due to be published in 2007.

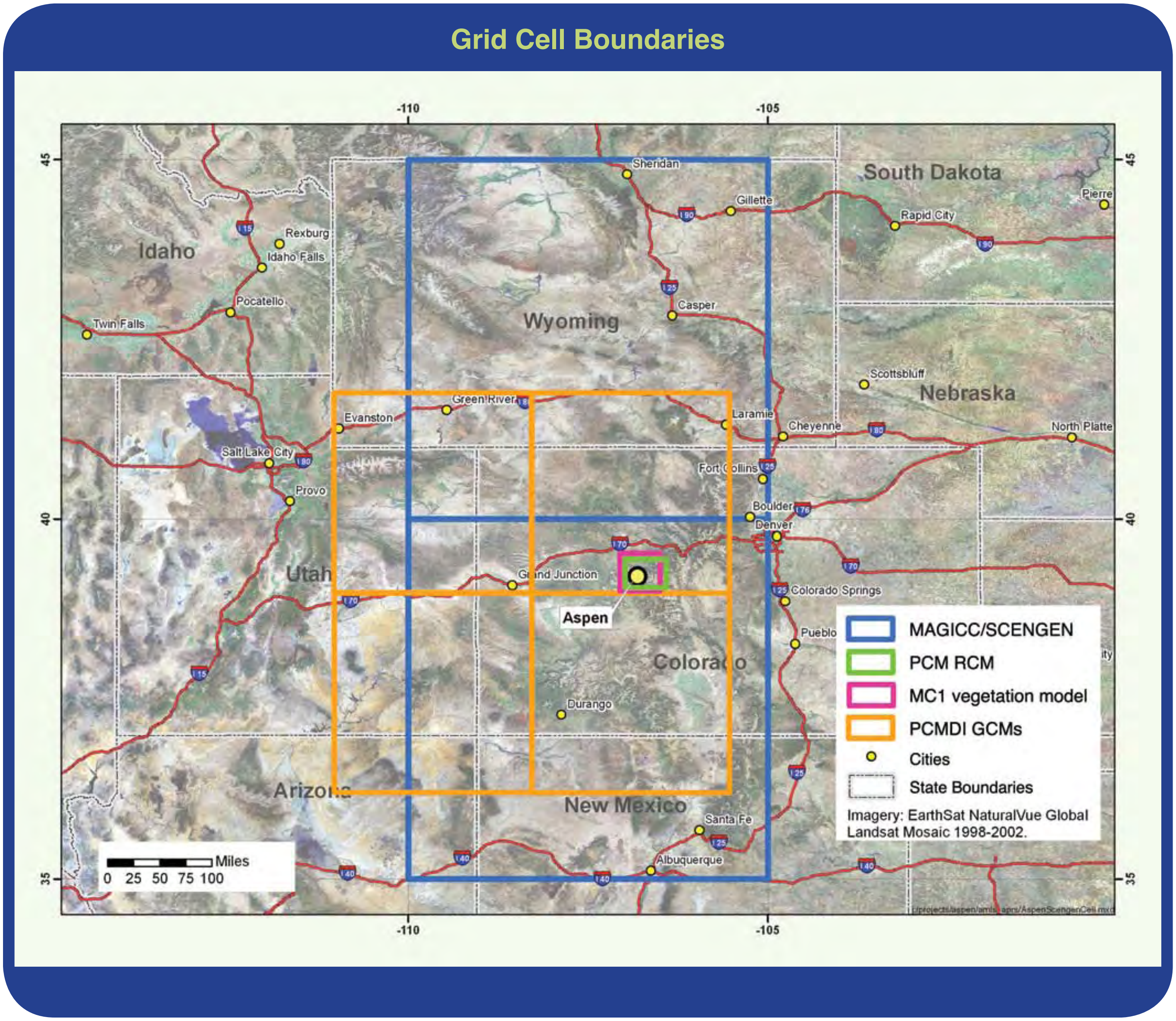


FIGURE 2.7: **Grid cell boundaries for four modeling approaches used in this study.** MAGICC/SCENGEN: utilized in the climate change analysis for the Aspen study area and SRM implementation in Chapters 2 & 3 (2 grid cells measuring approximately 300 x 300 miles [482 x 482 km] each; 105.0-110.0ºW and 35.0-45.0ºN). PCM RCM: utilized in the regional climate modeling in Chapter 2 (1 grid cell measuring approximately 22 x 22 miles [36 x 36 km]; 106.47-106.90ºW and 39.10-39.45ºN). MC1 vegetation model: utilized in the vegetation modeling in Chapter 4 (1 grid cell measuring approximately 30 x 30 miles [48 x 48 km]; 106.5-107.0ºW and 39.0-39.5ºN). PCMDI GCMs: utilized in Appendix C (4 grid cells measuring approximately 185 x 185 miles [300 x 300 km] each; 105.50-111.06ºW and 36.30-41.84ºN).

2.4.1 MAGICC/SCENGEN

To help address the three sources of uncertainty (GHG emissions, climate sensitivity, and regional climate), we utilized MAGICC/SCENGEN (Wigley, 2004). MAGICC is a one-dimensional model that estimates GHG concentrations and change in GMT and sea level. MAGICC allows users to select:

- GHG emissions scenarios
- Climate sensitivity (including parameters for 2 × CO_2 warming, aerosol feedbacks, carbon cycle, thermohaline circulation, and ice melt).

The companion program SCENGEN uses the regional pattern of *relative* changes in temperature and precipitation across 17 GCMs. The changes are expressed relative to the increase in GMT by the model. This pattern of relative change is preferable to simply averaging regional GCM output because it controls for differences in climate sensitivity across models; otherwise results from models having a high sensitivity would dominate.

SCENGEN estimates change in *average* temperatures and precipitation in grid boxes that are 5° across, roughly 300 miles (483 km) in length and width. In actuality, there is a lot of variation within the grid boxes because of differences in topography within the grid. Temperatures are typically lower at higher altitudes, whereas precipitation amounts can differ depending on altitude and whether the precipitation event is on the windward or leeward side of a mountain. SCENGEN does not capture those climatic differences within grid boxes. For this study, we used average projections from the grid box where Aspen is located and the adjacent grid box to the north because Aspen is close to the northern edge of its grid box (see Figure 2.7). This selection favors the western slope of the Continental Divide. The dimensions are 35 to 45°N and 105 to 110°W. The MAGICC/SCENGEN output for this region can be found in Section 2.5.1.

SCENGEN uses results from GCMs run for the IPCC Third Assessment Report (TAR) (IPCC, 2001a). These model runs were mostly done in the late 1990s. Although new GCM runs have been done for the Fourth Assessment Report (scheduled to be published in 2007), they have not yet been included in SCENGEN. However, Dr. Claudia Tebaldi and Dr. Linda Mearns of the National Center for Atmospheric Research (NCAR) supplied an analysis of what the new PCMDI model runs project for changes in Aspen's climate (see Section 2.4.4, Section 2.5.4, and Appendix C).

MAGICC/SCENGEN: Selection of Multiple GCMs

It is possible to use output from all 17 GCMs included in SCENGEN to examine how Southern/Central Rockies' climate is likely to change. Unfortunately, the 17 models are not all equal in their ability to simulate current climate. A model's ability to accurately simulate current climate is a test of its reliability in simulating the response of the climate system to increased GHG concentrations (Smith and Hulme, 1998). Therefore, a model's ability to simulate current climate better than other models is a measure of the model's *relative* reliability to simulate future changes in climate.

Typically in trying to determine a "best" model, there are models that do some things better than others, but no one model that does everything better. For example, one model may simulate El Nino events in the tropical Pacific very well, but do poorly with storm tracks over North America. Conversely, another model can simulate very credible storm tracks over North America but do less well simulating El Nino. A further complication in comparing how well models perform is whether or not they require flux adjustments (heat, water, etc. for the ocean-atmosphere interface) so they can more closely represent realistic current surface conditions (IPCC, 2001a).

Dr. Tom Wigley from NCAR, an advisor to this project, analyzed how well the models simulated current temperature and precipitation patterns for the Earth as a whole and for western North America. While we are most interested in the models' ability to simulate climate over the central Colorado Rockies, it is best to examine how well the models simulate climate over a larger region such as western North America because the capability of models to represent large-scale circulation patterns such as fronts are likely to be better captured. Care in this evaluation must be taken because the ability of a model to simulate climate in a particular region better than another model does not necessarily mean it is more reliable. For this reason, Dr. Wigley examined the models' simulations of current climate for the region around Aspen as well as of current global climate.

Dr. Wigley's report evaluating model capabilities is included in Appendix D. He recommended that the Aspen assessment use five models:

- CSIRO – Australia
- ECHAM3 – Max Planck Institute for Meteorology, Germany, version 3
- ECHAM4 – Max Planck Institute for Meteorology, Germany, version 4
- HadCM2 – Hadley Model, United Kingdom Meteorological Office, version 2
- HadCM3 – Hadley Model, United Kingdom Meteorological Office, version 4.

Appendix E presents an analysis of the five models' simulation of current climate in the two SCENGEN grid boxes that cover the Southern/Central Rockies.

The study uses three combinations of outputs from the five GCMs:

- The average of all five model projections of changes in average monthly temperature and precipitation
- The results of the driest model (ECHAM3)
- The results of a wettest model (HadCM2).

Note that the HadCM2, HadCM3, and ECHAM4 models best simulate current climate of the Southern/Central Rockies, particularly in terms of precipitation. By contrast, ECHAM3, and particularly CSIRO, have larger errors in simulating the amount and timing of current precipitation in the region. However, all five models simulate western North American climate relatively well (see Appendix D). Results from this analysis are in Section 2.5.1.

2.4.2 Regional Climate Modeling: PCM-RCM

The dynamical downscaling data utilized in this assessment have been provided by Dr. Ruby Leung of the Pacific Northwest Laboratory (Leung et al., 2003a, 2003b, 2004, 2005). Dr. Leung used the regional climate model MM5 "nested" within the Parallel Climate Model (PCM; Dai et al., 2004). Model outputs were generated for the roughly 20 mile (36 km) grid box containing Aspen, which is roughly bounded by 39.10 to 39.45°N to 106.47 to 106.90°W (Figure 2.7). The average elevation of this grid box is 10,600 ft (3,231 m). The GCM/RCM combination is abbreviated here as PCM-RCM. The output produced hourly and daily data for many 3 dimensional and 2 dimensional variables including temperature, precipitation, wind, relative humidity, radiative fluxes, cloud cover, etc. Future assessments within North America will benefit from the North American Regional Climate Change Assessment Program (NARCCAP), organized by Dr. Linda Mearns from NCAR, which will greatly extend the range of regional climate analysis capabilities utilizing models such as MM5 with a set of GCMs. Output from the PCM-RCM (see Section 2.5.2) was used in the analysis in Chapter 3.

2.4.3 Statistical Downscaling: SDSM

The purpose of statistical downscaling is to establish a statistical relationship between large-scale GCM data and smaller scale climate variables in order to estimate how climate at a specific location may change. The technique can be applied at a regional scale of multiple grid boxes, often referred to as large-scale, or down to a specific site (such as a weather station), small-scale. The approach assumes that the statistical relationship between the climate variables in a GCM and observed climate at a specific location will not change with climate change. The disadvantage of this approach is that the assumption about a constant statistical relationship could be wrong. The advantage is that statistical downscaling can be used to develop a scenario for a specific location. Dr. Robert Wilby, a member of the study team for this assessment, applied the Statistical Downscaling Model (SDSM). He used the output from the HadCM3 model (Climate Model developed at Hadley Center, United Kingdom Meteorological Office) for the grid cell containing Aspen and downscaled it to the SNOTEL weather station at Independence Pass.[6] The SDSM analysis is summarized in Section 2.5.3; the method and calibration for this analysis is in Appendix B. As with RCMs and global modeling, reliable results are more difficult for precipitation than for temperature (Leung et al., 2003c).

2.4.4 PCMDI Multimodel GCMs with Probability Distributions

The PCMDI multimodel output (See Section 2.5.4 and Appendix C) provided to this study by Drs. Claudia Tebalidi and Linda Mearns from NCAR uses a Bayesian statistical model that synthesizes the information contained in an ensemble of different GCMs (up to 21), run under historical and future scenarios, into Probability Distribution Functions (PDFs) of temperature and precipitation change (see results in Section 2.5.4). This approach allowed us to examine the differences between emissions scenarios and to compare seasonal change relative to present climate (Tebaldi et al., 2004).

Historical observed data are used to assess model reliability in representing current climate. In addition, the criterion of "convergence" bears weight in determining how individual GCMs contribute to the overall estimate, in the sense that projections that agree with one another within the ensemble will receive relatively more weight in the final estimates of the PDFs than projections that appear as outliers (Tebaldi et al., 2004).

The analysis is performed at a regional scale, i.e. we first area-averaged the 4 gridpoints surrounding Aspen, for each GCM contributing data, into regional means of temperature and precipitation. Then the individual models' projection are combined. Ultimately, for each season
and for each SRES scenario (A2 = high emissions, A1B = mid-range emissions and B1 - low emissions) we determine as our final output Probability Distribution Functions (PDFs) of temperature and precipitation change ("change" is defined as the difference between two 20-year means, e.g. 1980-1999 vs. 2080-99)[7]. The four grid boxes surrounding Aspen utilized in this approach are shown in Figure 2.7.

---

6. The Independence Pass station was used because it collects data year-round and provides the full suite of data needed to run the snow models. Aspen Mountain also collects climate data, but only from December 1 through March 31. Since data are needed for the fall (so as to estimate build-up of snowpack), we used Independence Pass data. Temperatures were adjusted for differences in elevation. Independence Pass was used instead of the data from the Aspen water treatment plant for two reasons: one, Independence Pass is in the mountains, therefore its record of temperature and precipitation will be closer to Aspen Mountain than the data in the city; two, the measuring station in the city was moved during the period of record, making the data less reliable.

7. Note: of the three emissions scenarios used in the PCMDI GCM multimodel analysis, two (A1B and B1) are the same as used in the MAGCICC/SCENGEN runs. The third, A2 is similar to A1FI – both are highest in emissions of the main IPCC SRES scenarios.

2.5 PROJECTIONS OF CLIMATE CHANGE

2.5.1 MAGICC/SCENGEN

Figure 2.8 presents the estimated change in temperature (in Fahrenheit) for the Southern/Central Rockies by 2030 (relative to the 1990's) using the A1B (middle emissions) scenario and assuming a climate sensitivity of 5.4°F (3°C). The first five bars are individual models; the last bar is the five model average. Under this scenario, the average model-calculated warming is 3.6°F (2.0°C), with a range of 3.2 to 4.5°F (1.8 to 2.5°C).

Figure 2.9 presents the estimated changes in precipitation for the same scenario. All five models project a decrease in annual precipitation for the Southern/Central Rockies.[8] The calculated decreases range from 1% to 18%, with the five model average projecting an 8% decrease. The magnitude of the decrease is partially a result of the scenario and a result of the increase in GHGs and aerosols (e.g., SO_2). So, if aerosol increases are not as large as in the A1B scenario, the decrease in precipitation would not be as large. To test the sensitivity of the results to the inclusion of aerosols, a sensitivity analysis was run using model simulations of the A1B scenario, but assuming no aerosols. Note that the change in precipitation during the current snow season, October through March, ranges from an increase of 5% to a decrease of 13%. The models tend to project decreased precipitation in the summer (except August) and increases in the winter.

Figures 2.10 and 2.11 display the temperature and precipitation changes for the A1B scenario by 2100, assuming 5.4°F (3°C) sensitivity. By 2100, these five models project a 9°F (5°C) warming, with a range of 7 to 11°F (4 to 6°C). The average change in annual precipitation is slightly less in

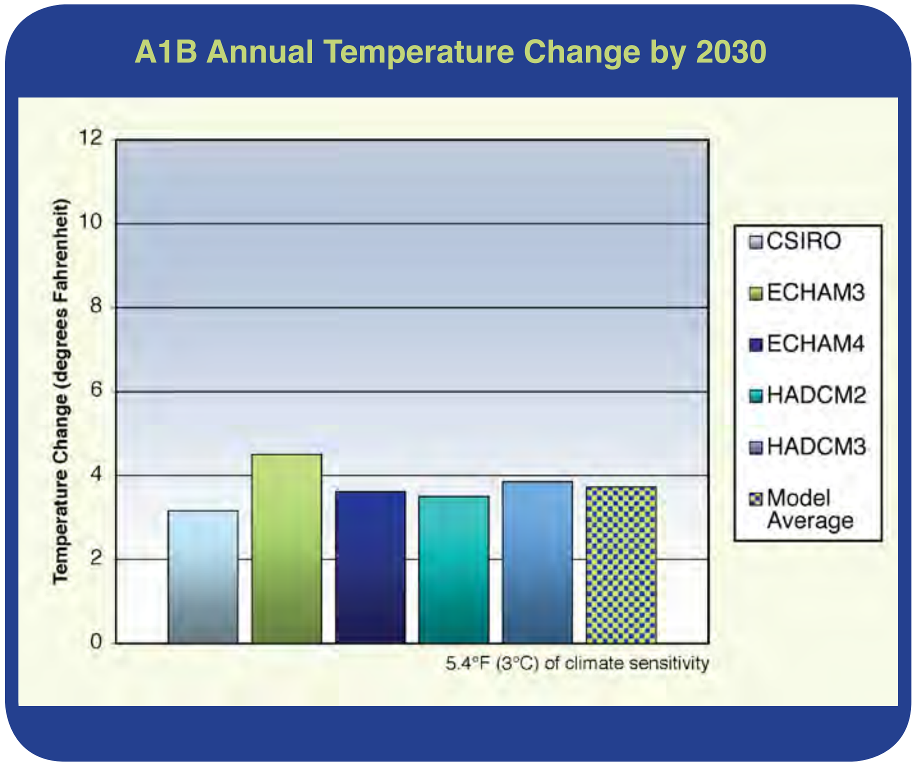


FIGURE 2.8: **Temperature increases for the Southern/Central Rocky Mountain region as applied to Aspen by 2030 under the A1B (medium emissions) scenario and 5.4°F (3°C) sensitivity.** CSIRO = climate model developed by the Australian Commonwealth Scientific and Industrial Research Organisation; ECHAM3 and ECHAM4 = climate models developed by the Max Planck Institute for Meteorology, Germany; HADCM2 and HADCM3 = climate models developed at Hadley Model, United Kingdom Meteorological Office. These 5 models were selected from the 17 GCMs in MAGICC/SCENGEN by criteria established by Tom Wigley.[9]

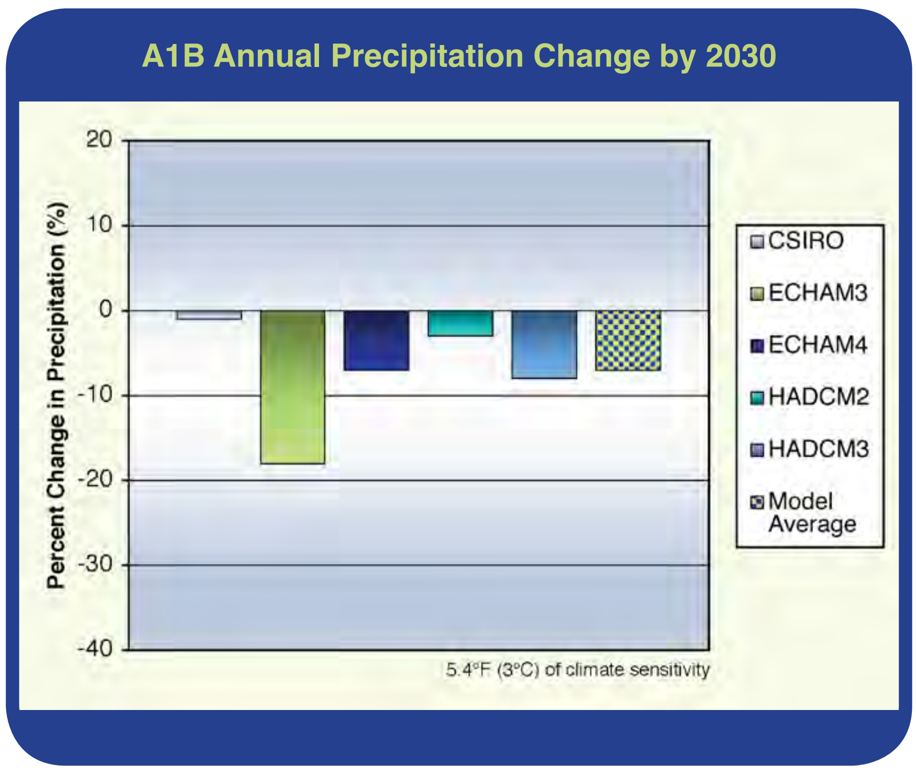


FIGURE 2.9: **Precipitation decreases for the Southern/Central Rocky Mountain region as applied to Aspen by 2030 under the A1B (medium emissions) scenario and 5.4°F (3°C) sensitivity.**

8. This consistency across models should be interpreted with extreme caution. There is substantial uncertainty about how precipitation will change; enough to suggest some caution about concluding that a reduction in precipitation is likely. Nevertheless, five models projecting a decrease clearly indicate the potential for a reduction in precipitation.

9. See Wigley's report in Appendix C

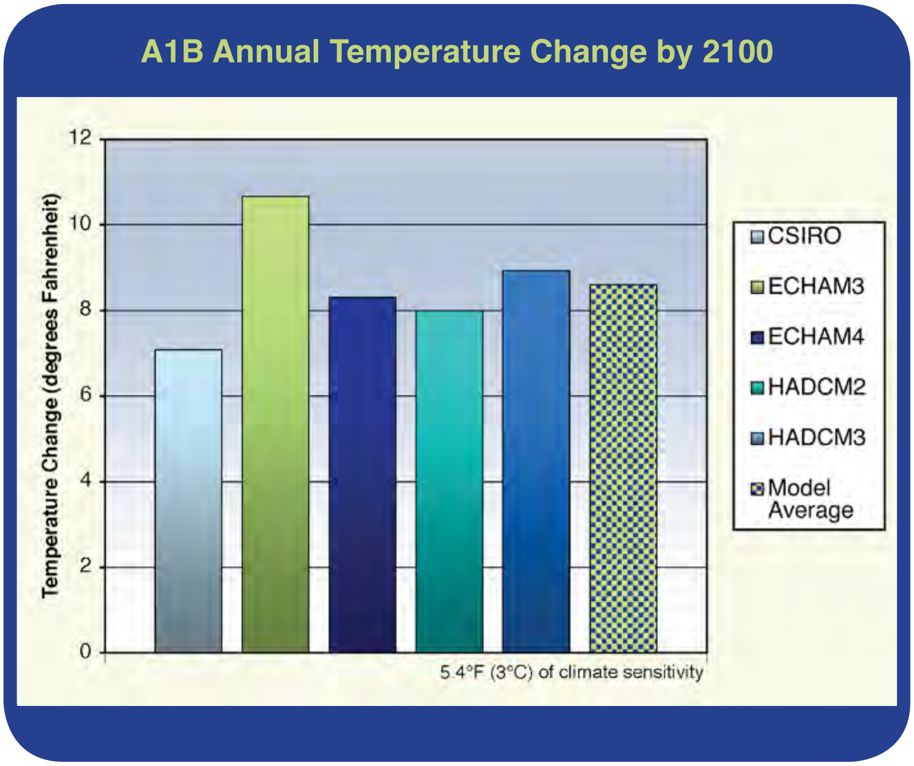


FIGURE 2.10: **Temperature increases for the Southern/Central Rocky Mountain region as applied to Aspen by 2100 under the A1B (medium emissions) scenario and 5.4°F (3°C) sensitivity.**

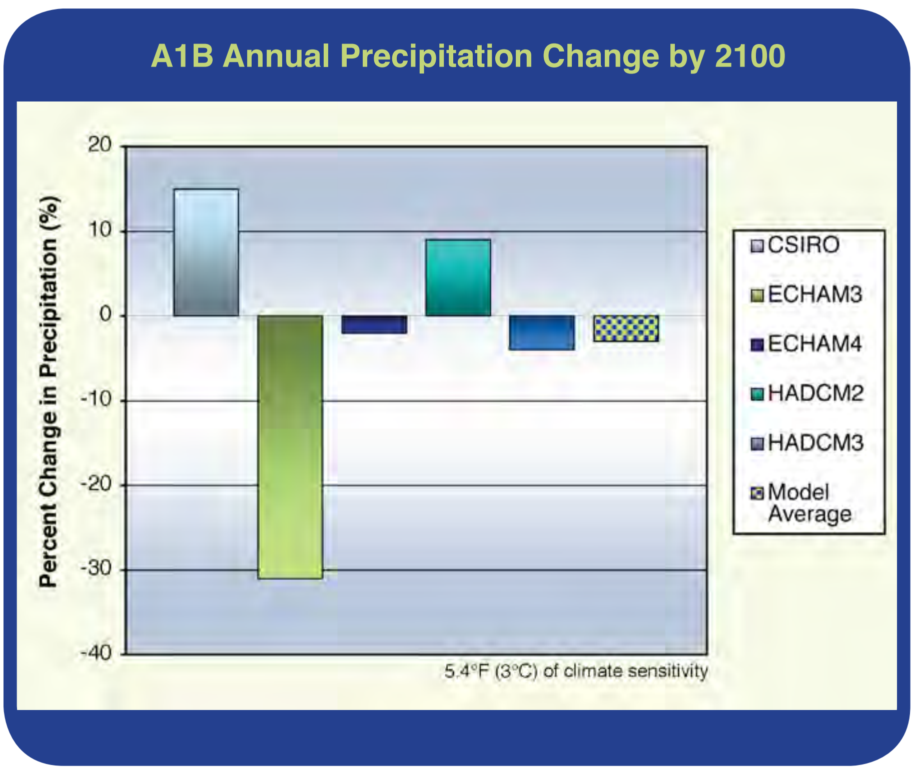


FIGURE 2.11: **Precipitation changes for the Southern/Central Rocky Mountain region as applied to Aspen by 2100 under the A1B (medium emissions) scenario and 5.4°F (3°C) sensitivity.**

the 2100 time period than in the 2030's: -3% and the range of change across the climate models is much greater. The wettest model estimates a 15% increase in annual precipitation and the driest model has a 31% decrease in precipitation. By 2100, aerosol emissions in the A1B scenario have declined substantially and apparently have little effect on precipitation. By this time, almost all of the changes in climate appear to be the result of increased GHG concentrations. It is interesting that by 2100, with low aerosol concentrations, two of the five models used in this analysis project an increase in precipitation rather than a decrease.

This study also uses different GHG emissions scenarios to reflect a wide range of possible future emissions, and different climate sensitivities to reflect a reasonably wide range of potential changes in global climate in response to increased GHG concentrations (see discussion above on GHG emissions and climate sensitivity). Results for temperature for 2030 and 2100 are presented in Tables 2.1(a) and 2.1(c). Precipitation would also change (because of the assumption in pattern correlation that precipitation increases or decreases as a function of change in global mean temperature) (Tables 2.1(b) and 2.1(d). The A1FI scenario, the high GHG emissions scenario, leads to an almost 60% larger temperature increase in this region in the year 2100 as compared to the results for the A1B scenario. In contrast, the B1 scenario, the low GHG emissions scenario, leads to a projection of almost 30% less warming. Increasing the climate sensitivity from its mid-range value (5.4°F, or 3°C) to the upper-end value that is traditionally assumed (i.e., 8.1°F or 4.5 C) is projected to augment the mean temperature increase by about 30%. Reducing the sensitivity from its mid-range value to the lowest plausible value (i.e., 2.7°F or 1.5°C) is projected to reduce the mean temperature increase by just over 40%.[10]

10. The changes in temperature resulting from different assumptions about sensitivity do not exactly match the percentage change in global temperature sensitivity because of the role of aerosols. Thus, the percentage changes vary slightly depending on the emissions scenario. For example, the A1FI scenario has slightly lower percentage changes in temperature using the different climate sensitivities than does the A1B scenario, while the B1 scenario has slightly higher changes in temperature. The differences caused by the different emissions scenarios are only a few percent.

Projected Change in Temperature by 2030
in Degrees Fahrenheit

Sensitivity		A1B	
(ºC)	(ºF)	Average (ºF)	Range (ºF)
1.5	2.7	2.3	2.0 to 2.9
3.0	5.4	3.8	3.2 to 4.5
4.5	8.1	4.7	4.0 to 5.6

TABLE 2.1A: **Projected change in mean annual temperature for the Southern/Central Rocky Mountain region as applied to Aspen by 2030 from MAGICC/SCENGEN, in degrees Fahrenheit.**

Projected Change in Total Annual Precipitation for 2030
Percentage Change

Sensitivity		A1B	
(ºC)	(ºF)	Average	Range
1.5	2.7	-5	-11 to -1
3.0	5.4	-7	-18 to -1
4.5	8.1	-9	-23 to -1

TABLE 2.1B: **Projected percent change in total annual precipitation for the Southern/Central Rocky Mountain region as applied to Aspen by 2030 from MAGICC/SCENGEN.**

Projected Change in Temperature by 2100
in Degrees Fahrenheit

Sensitivity		SCENARIOS					
		A1FI		A1B		B1	
(ºC)	(ºF)	Average (ºF)	Range (ºF)	Average (ºF)	Range (ºF)	Average (ºF)	Range (ºF)
1.5	2.7			4.9	4.1 to 6.1		
3.0	5.4	13.7	11.3 to 16.9	8.6	7.0 to 10.6	6.3	5.2 to 7.7
4.5	8.1			11.3	9.2 to 14.0		

TABLE 2.1C: **Projected change in mean annual temperature for the Southern/Central Rocky Mountain region as applied to Aspen by 2100 from MAGICC/SCENGEN, in degrees Fahrenheit.**

Projected Change in Total Annual Precipitation for 2100
Percentage Change

Sensitivity		SCENARIOS					
		A1FI		A1B		B1	
(ºC)	(ºF)	Average	Range	Average	Range	Average	Range
1.5	2.7			-2	-18 to 9		
3.0	5.4	-4	-49 to 24	-3	-31 to 15	-2	-23 to 11
4.5	8.1			-20	-41 to 20		

TABLE 2.1D: **Projected percent change in total annual precipitation for the Southern/Central Rocky Mountain region as applied to Aspen by 2100 from MAGICC/SCENGEN.**

For all combinations of emissions scenarios and climate sensitivities in 2030, all of the climate models project a decrease in precipitation. However, as noted above, by 2100 two out of five of the climate models estimate that precipitation will increase. In all cases, the higher the emissions or the higher the sensitivity, the greater the absolute change in precipitation. Interestingly, the range of change in precipitation, while sensitive to emissions scenarios and climate sensitivity, appears to be most sensitive to differences across GCMs. This indicates that the amount precipitation will change is uncertain. In contrast, it is certain that temperature will continue to rise while exactly how much remains uncertain.

To develop climate change scenarios for Aspen, the study combined the estimated changes in monthly temperatures and precipitation from the GCMs with observed weather data from Independence Pass and Aspen Mountain (see Section 3.3). This effectively grounds the climate change scenarios in the climatology for Aspen. The scenarios will have a similar seasonal pattern of temperatures and precipitation, but will be warmer and either drier or wetter, depending on the scenario, than the observed climate.

The models project consistent seasonal changes, although this agreement across models should be interpreted with caution. Most of the models project increased precipitation in January and February, with precipitation decreasing until it reaches its maximum decrease in July. The ECHAM model is an exception, projecting decreased precipitation in all winter months, but an increase in July. All the models project increased precipitation in August. This could be because the models project an increase in the monsoon. The models tend to project decreasing precipitation through December, although CSIRO model projects increased precipitation in the fall and early winter.

The models estimate more consistent changes in temperature. All project increased temperatures for all months. The highest temperature increase is estimated for June

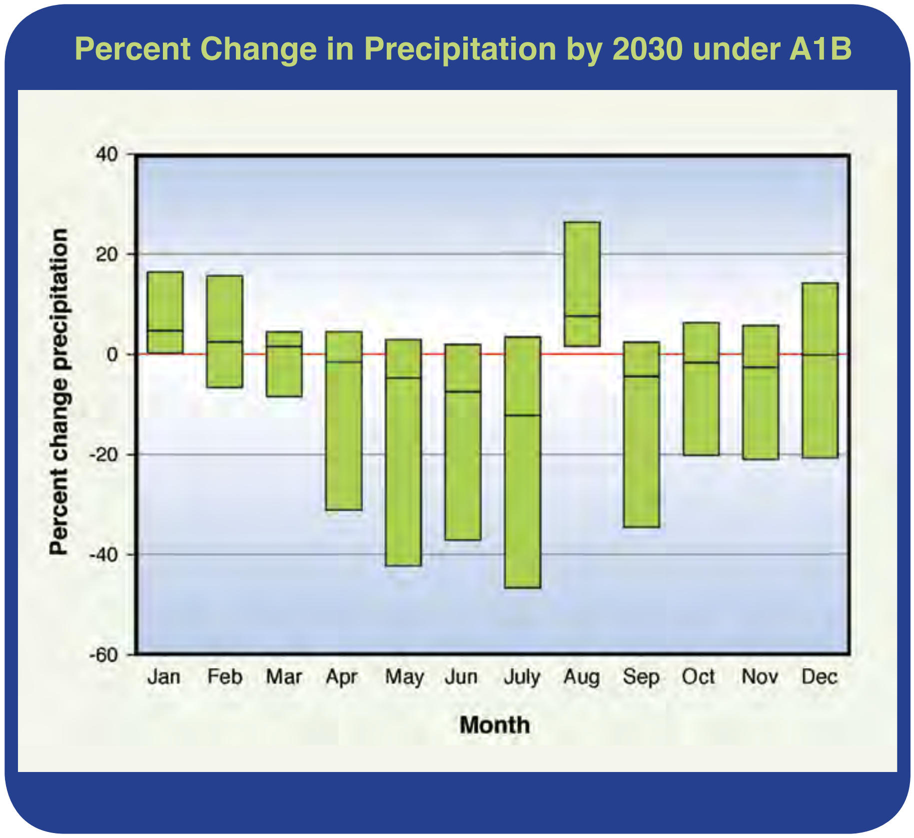


FIGURE 2.12: **Percent change in monthly precipitation for the Southern/Central Rocky Mountain region as applied to Aspen by 2030 under the A1B scenario for 5.4°F (3°C) sensitivity.** Each box plot represents the maximum (top of box), average (center line), and minimum (bottom of box) of a five model set from the MAGICC/SCENGEN analysis.

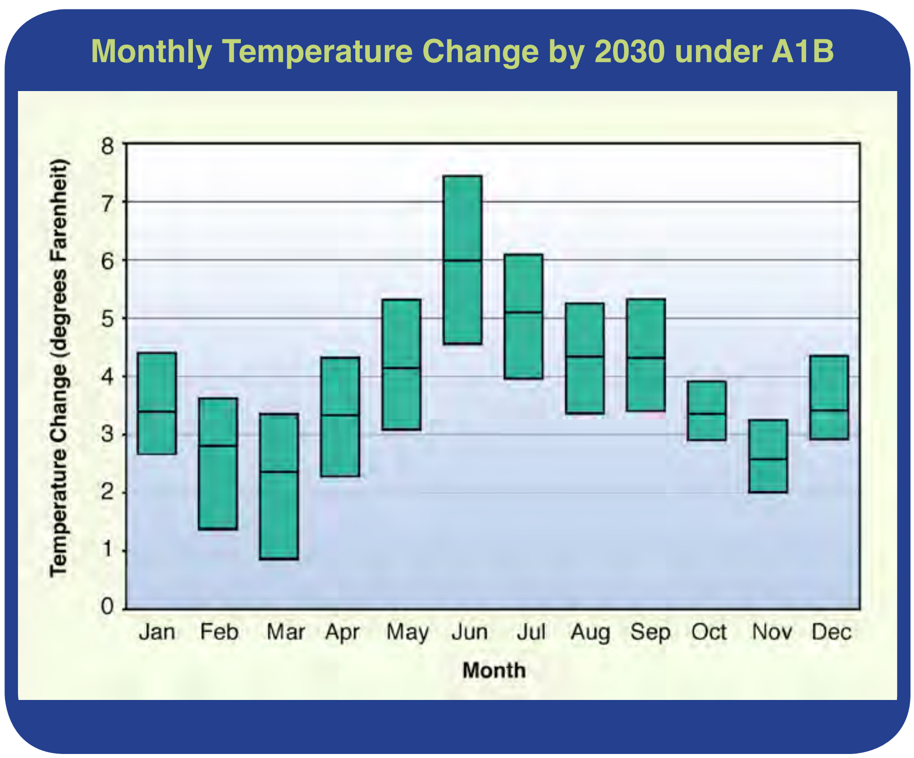


FIGURE 2.13: **Monthly temperature change for the Southern/Central Rocky Mountain region as applied to Aspen by 2030 under the A1B scenario for 5.4°F (3°C) sensitivity, in degrees Fahrenheit.** Each box plot represents the maximum (top of box), average (center line), and minimum (bottom of box) of a five model set from the MAGICC/SCENGEN analysis.

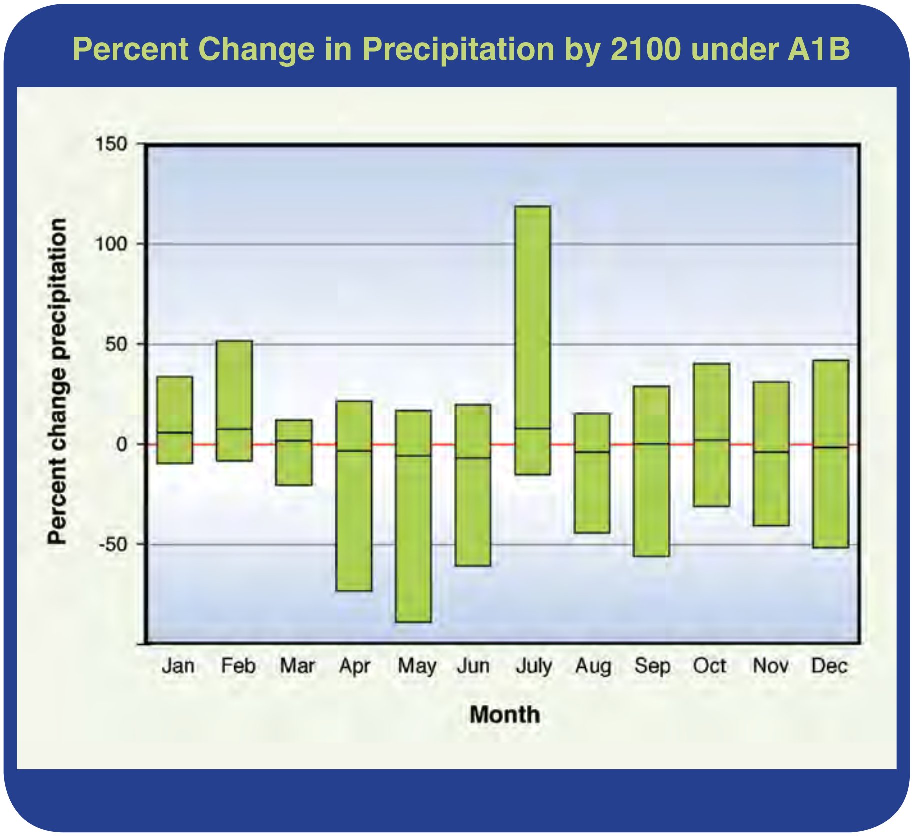


FIGURE 2.14: **Percent change in monthly precipitation for the Southern/Central Rocky Mountain region as applied to Aspen by 2100 under the A1B scenario for 5.4°F (3°C) sensitivity.** Each box plot represents the maximum (top of box), average (center line), and minimum (bottom of box) of a five model set from the MAGICC/SCENGEN analysis.

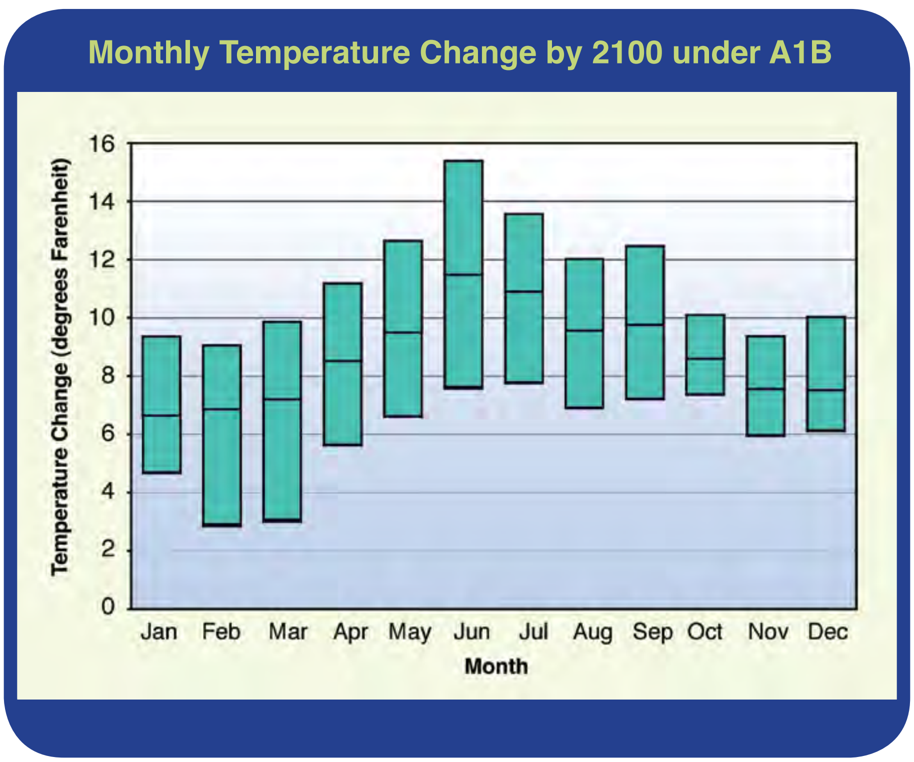


FIGURE 2.15: **Temperature change by 2100 for the Southern/Central Rocky Mountain Region as applied to Aspen under the A1B scenario for 5.4°F (3°C) sensitivity, in degrees Fahrenheit.** Each box plot represents the maximum (top of box), average (center line), and minimum (bottom of box) of a five model set from the MAGICC/SCENGEN analysis.

in both the 2030 and 2100 results. The lowest temperature increases are estimated for March and November in 2030, but in 2100 (A1B), the lowest increase is in January. Increases in December through February temperatures are close to projected annual average changes. Figures 2.12 –2.15 show box plots of monthly output for A1B temperature and precipitation for 2030 and 2100.

2.5.2 Regional Climate Modeling

Figures 2.16 and 2.17 display PCM RCM estimated increases in maximum temperature (Tmax), minimum temperatures (Tmin), while Figure 2.18 shows change in precipitation. The figures compare average projections of temperature and precipitation in 2030 (averaging model simulations for 2020 to 2040) compared to the base period in the RCM of 1990 (1980-2000).

The RCM projects an increase in temperature for each month except November, which is difficult to explain (Ruby Leung, Pacific Northwest Laboratory, personal communication, November 17, 2005). On average, total annual precipitation is projected not to change by very much, although the RCM projects a decrease in precipitation from December through March, and an increase in April and again during late summer and early fall.

The RCM results are quite different from the MAGICC/SCENGEN results, particularly in seasonality. The RCM projects the largest temperature increases in February and March, whereas the MAGICC/SCENGEN set of GCMs project the largest temperature increases in June and July, as does the PCMDI multimodel analysis and the statistical downscaling. Furthermore, the RCM projects decreased precipitation in December through March, while many, but not all of the GCMs project increases in January and February.

2.5.3 Statistical Downscaling

The projections of temperature and precipitation changes using statistical downscaling (SDSM) based on the HadCM3 model are displayed in Table 2.2. Note that different emissions scenarios were used.[11] The A2 scenario has CO_2 concentrations between A1B and A1FI by 2100, while the B2 scenario has CO_2 concentrations by 2100 between A1B and B1. The results are downscaled to Independence Pass, with an elevation of 10,600 feet (3,231 m).[12] Since there is a viable correlation between Independence Pass and the Aspen Mountain weather station during the months it operates (see Chapter 3), it is reasonable to assume that the changes in temperature and precipitation would be similar to Aspen Mountain.

The SDSM results are more consistent with the MAGICC/SCENGEN monthly projections than the RCM results, but there are still significant differences. SDSM projects generally larger temperature increases in the summer than in the winter, but with substantial month-to-month variation. The SDSM results also tend to estimate increased winter precipitation and decreased summer precipitation, with a pronounced decrease in June, whereas the GCMs project the largest decrease in monthly precipitation in July, but also a decrease in June.

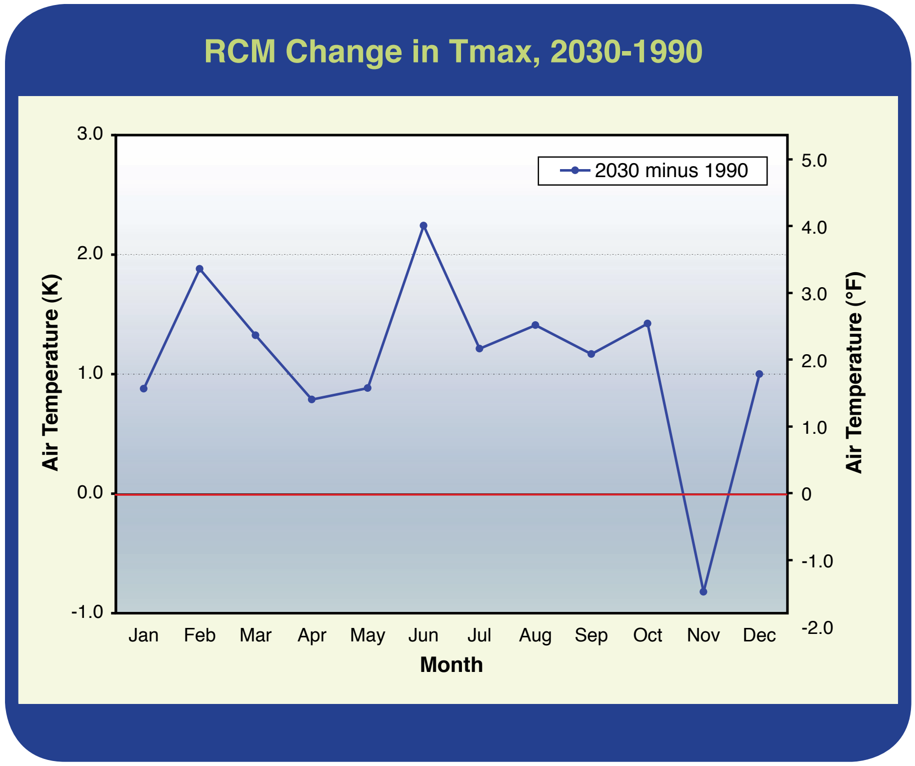


FIGURE 2.16: **Estimated change in Tmax from PCM RCM for 2030 relative to 1990 for the Aspen grid box.**

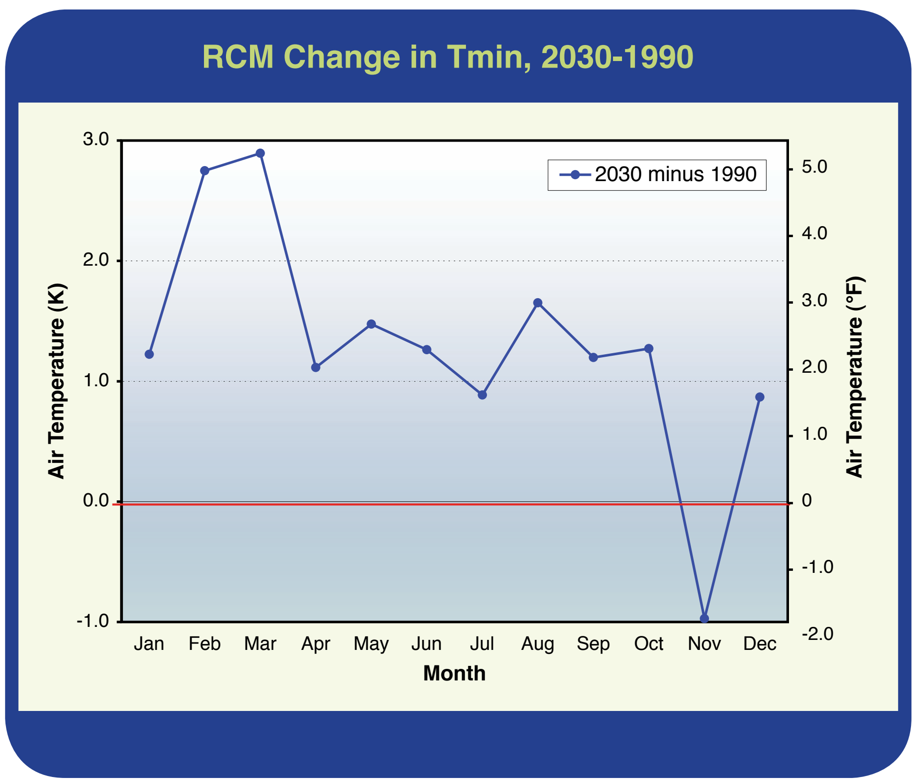


FIGURE 2.17: **Estimated change in Tmin from PCM RCM for 2030 relative to 1990 for the Aspen grid box..**

2.5.4 PCMDI Multimodel GCMs with Probability Distributions

Figure 2.19 shows the seasonal temperature change under the A2 emissions scenario, displayed as probability distributions for each of the seasons (e.g. December, January, February (DJF)) for the late 21st century. Broad distributions indicate greater variance in projected temperature change; curve peaks represent the mean temperature change for a

11. The SDSM model has only been applied to the A2 and B2 runs from the Hadley model

12. See Section 2.4.3 for a discussion of why Independence Pass was used.

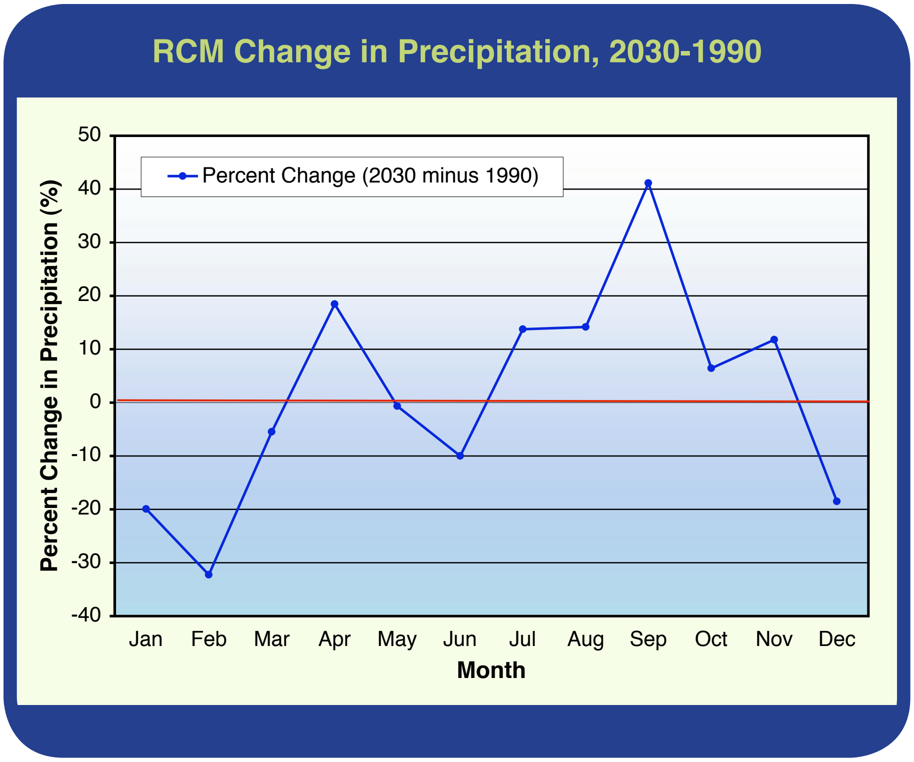


FIGURE 2.18: **Estimated change in precipitation from PCM RCM for 2030 relative to 1990 for the Aspen grid box.**

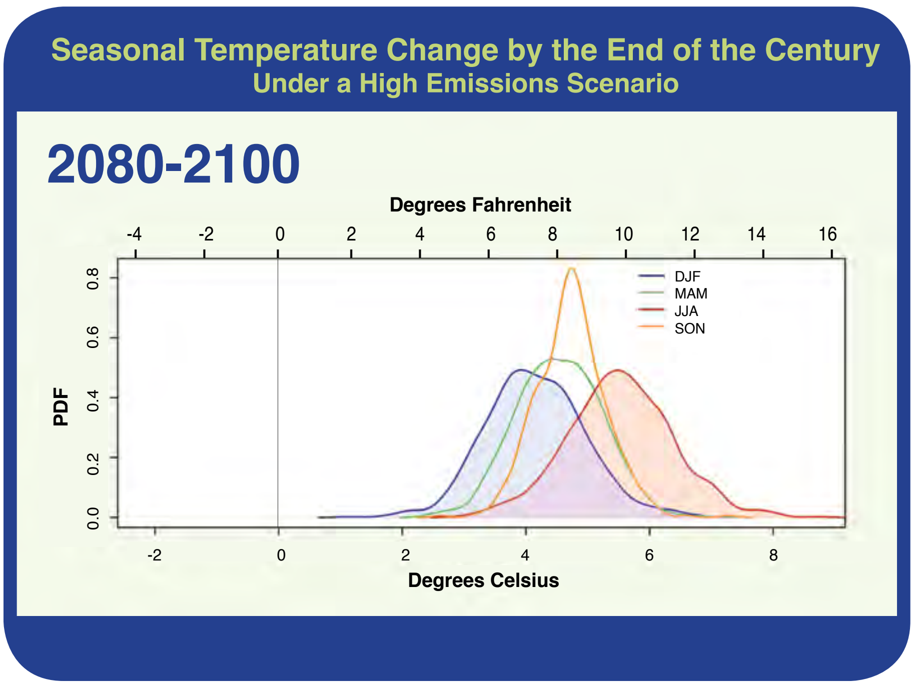


FIGURE 2.19: **Mean temperature change for the 4 grid box area surrounding Aspen under a high emissions scenario (A2), comparing seasons for the 2080-2100 period.** Zero line represents no change in temperature; peaks further to the right indicate a greater increase in temperature for the months identified. Y-axis is a function of likelihood. Shaded plots suggest greater warming in summer (red) vs. winter (blue) months. DJF = December, January, February; MAM = March, April, May; JJA = June, July, August; SON = September, October, November. (Source: Plots made for the Aspen project by C. Tebaldi and L. Mearns at NCAR utilizing data from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) IPCC Data Archive at Lawerence Livermore National Laboratory. Tebladi et al., 2004; Tebaldi et al., 2005)

Projected Changes in Temp and Precip for Aspen using Statistical Downscaling

Scenario	Temp. increase (°F)	Precip. change (%)
B2 2030	2.0	0
A2 2030	1.4	0
B2 2100	4.0	-9
A2 2100	5.9	-7

TABLE 2.2: **Projected changes in temperature and precipitation for Aspen using statistical downscaling from HadCM3 for a high (A2) and low (B2) emissions scenario.**

given season. Additional results for early and mid century are included in Appendix C. In all three examples, the fall (September, October, November (SON)) months have the least variance (tightest distribution about the mean). Its also interesting to note that for all three time periods and all seasons, temperature is higher than the current climate. By 2100, the difference in temperature between the seasons becomes greater. Note also that the summer (June, July, August (JJA)) warms proportionately more than all other seasons, with winter (DJF) warming the least. These results are similar to those from the A1B MAGICC/SCENGEN analysis where summer warms the most and winter the least (Figures 2.12 and 2.14). The SDSM results also indicate summer months having the greatest warming (see Appendix B).

Precipitation change under the A2 emissions scenario, again comparing seasons, shows that summer has the greatest variance (broadest probability distribution) and spring the least (most narrow probability distribution). All seasons in the 2000-2020 time period are close to present mean precipitation, but as the century progresses, winter shows an increase in precipitation, fall not much change, and spring a slight decrease. (See Appendix C for more results)

2.6 SUMMARY

All of the SRES scenarios analyzed using the different modeling approaches project a substantial increase in temperatures for the region, but different assumptions about greenhouse gas emissions and climate sensitivity result in different estimates of the magnitude of warming. In addition, downscaling techniques project slightly less warming than the MAGICC/SCENGEN GCMs.

Results from MAGIC/SCENGEN show that different assumptions about emissions can change estimated temperature increases over the Southern/Central Rockies by as much as 7°F (4°C). Different assumptions about climate sensitivity can change the estimated warming by 5.4°F (3°C). The differences among the individual climate models are about 3.5°F (2°C). To be sure, only five models were examined.

The RCM and SDSM estimates are somewhat lower than the GCM estimates, but this could be because different climate models and emissions scenarios were used. In general, differences across climate model projections of temperature are mainly the result of different emissions and climate sensitivities. There is consistency across all the modeling approaches that Aspen will warm significantly.

The seasonality of temperature changes is less certain. The PCMDI GCMs and MAGICC/SCENGEN climate models project the largest warming in the summer and the least warming in winter. Output from one application of statistical downscaling agrees, but application of a regional climate model projects the most warming in the winter. So, there does not appear to be a consensus across the models. It also possible that reduced snowpack in the spring and fall will lead to the most warming in those seasons.

On average, the MAGICC/SCENGEN models project a decrease in annual precipitation in 2030, but have mixed results by 2100. The decrease in precipitation in 2030 for the M-S runs is largely the result of the assumption in the emissions scenario we examined that sulfate aerosol concentrations will increase significantly before decreasing. There is even more uncertainty about the seasonality of precipitation changes. Many of the MAGICC/SCENGEN GCMs, as well as the statistically downscaled model and PCMDI GCMs, project decreased precipitation in the summer and increases in many winter months. The regional climate model projects the opposite: increased precipitation in mid to late summer and decreases in winter precipitation.

While it is virtually certain that temperature will continue to rise, whether precipitation will increase or decrease is uncertain.

Climate models' estimates of changes in precipitation are generally less reliable than the models' projections of temperature. We are confident that high latitude areas, well to the north of Aspen, will on average see increased precipitation, while areas well south of Aspen, could well see decreases in precipitation. In general, there is uncertainty about whether the Central Colorado Rockies will see increased or decreased precipitation and how the seasonality will change.

In spite of these uncertainties, there is certainty that climate is changing. A continued warming of the climate is highly likely. This will affect climate patterns and snowpack. The following sections of the report examine how snowpack, ecosystems, socioeconomics, and streamflow in the Aspen area could be affected by the scenarios described in this chapter.

3.1 INTRODUCTION

While Chapter 2 covered the history and potential future of Aspen's climate in terms of temperature and precipitation, this chapter focuses on how climate change could affect snow conditions.

The study team developed and applied snowpack models and determined relationships with key climate variables to analyze how snowpack in the four area ski mountains could be affected under the climate scenarios. Our objectives were to estimate the length of the ski season, the timing of snowpack buildup and melt, the snow depth and coverage at specific times, and the snow quality at different locations and times.

Snow accumulation at the base area begins approximately 1 week later by 2030 and anywhere from 1.5 to 4.5 weeks later by 2100. All model runs show a substantial impact on early season snow depths at the top of the mountain. This is because of October snowfall melting off and the precipitation coming as rain rather than snow. Melt at the base area begins 4 to 5 days earlier by 2030 and 2.5 to 5 weeks earlier by 2100. The length of the snow season is about 1.5 weeks shorter by 2030 and 4 to 10 weeks shorter by 2100. By 2100, it is unlikely that a winter snowpack persists at the base area, with the exception of the B1 emissions scenario. In general, a 15% increase in precipitation compensates for a 2.7°F (1.5°C) warming, such that there is little change in snow depth. Snow quality remains high, with less than a 20% increase in the density of the top few inches of snow.

The Modeled Area Defined for The SRM Implementation

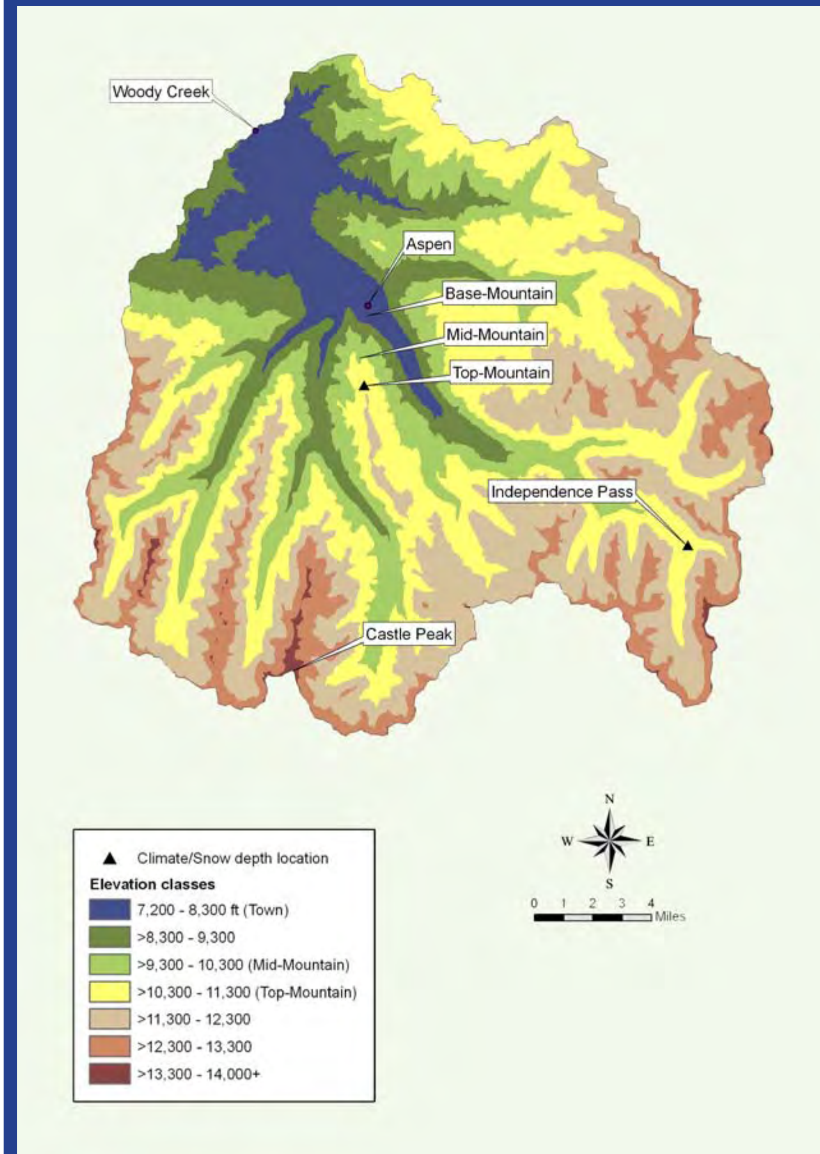


FIGURE 3.1: **The modeled spatial extent defined for the SRM implementation.**

3.2 SNOW MODELS

The Snowmelt Runoff Model (SRM), developed and maintained by the U.S. Department of Agriculture, Agricultural Research Service (Martinec, 1975; Martinec et al., 1994; model and documentation available at http://hydrolab.arsusda.gov/cgi-bin/srmhome) was used as the main model to examine four ski areas in the Aspen area, and the SNTHERM model to obtain detailed information on spatial variability about Aspen Mountain (Jordan, 1991).

SRM is focused on surface processes, and is specifically designed to assess snow coverage and snowmelt runoff patterns. The model uses a temperature-index method, which is based on the concept that changes in air temperature provide an index of snowmelt. SRM requires geographic information systems (GIS) information (including a digital elevation model, land use/land cover, and estimates of snow cover) for implementation. Appendix F provides a detailed description of the GIS and remote sensing processes used to generate the topographic, land cover, and estimates of snow cover that are needed by the model. The model area is subdivided into elevation zones, which enables SRM to generate refined estimates of snowpack coverage and melt in watersheds with large vertical relief, such as the Roaring Fork.

SRM was used to estimate the length of the ski season, the timing of snowpack accumulation and melt, and the snow depth and coverage (derived from satellite imagery) at a given time. The modeled spatial extent for this study was dictated by outlining an area that encompassed the four ski mountains, and then determining the farthest upstream confluence that would capture all the snowmelt from this area. The confluence of the Roaring Fork and Woody Creek was determined to be the farthest upstream confluence meeting this condition. This implied that our modeled area would span a vertical distance of approximately 7,000 ft, (2,134 m) ranging from the confluence (elevation 7,300 ft [2,225 m]) to the highest elevation on the upstream watershed, or the 14,265 ft (4,438 m) summit of Castle Peak. Vertical resolution of a 1,000 ft (305 m) was employed, necessitating seven elevation zones of 1,000 ft each (Figure 3.1). SNTHERM sacrifices simplicity for complicated measurements and algorithms. The model was developed by Rachel Jordan, U.S. Army Corps of Engineers, Cold Regions Research and Engineering Laboratory. SNTHERM is a process driven, one-dimensional energy and mass balance point model, as opposed to the more simplified temperature-index approach to modeling snowpack. Using meteorological variables, the model simulates snow density, grain size, snow depth, and snow temperature.

We used SNTHERM to estimate changes in snow density, snow depth, and how these characteristics change with landscape type for one climate scenario. For this study, we developed 12 landscape types from a combination of elevation, aspect, and vegetative cover. Elevation was either low (7,000 to 10,000 ft [2,134 to 3,048 m]), medium (10,000 to 12,000 ft [3,048 to 3,659 m]), or high (12,000 to 14,000+ ft [3658 to 4,267 m]). Aspect was defined to be either northerly or southerly, and vegetative cover was either with trees or without trees (Figure 3.2). SNTHERM is a point model, implying that model results apply only to the conditions at that point. The landscape types are used to extrapolate point results spatially, by accounting for energy balance differences unique to each landscape type (Anderson, 2005).

Map of the Defined Landscape Types Employed in the SNTHERM Model Runs

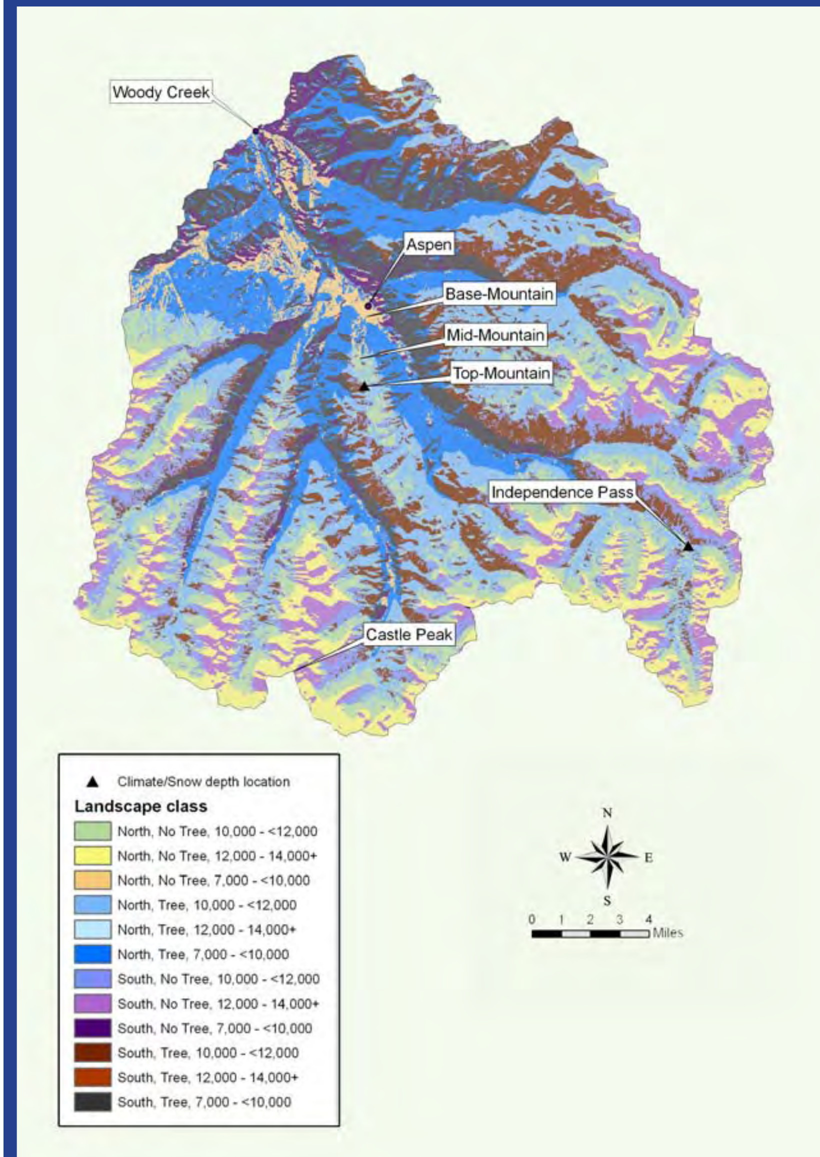


FIGURE 3.2: **Map of the defined landscape types employed in the SNTHERM model runs.**

3.3 HISTORICAL AND CURRENT CLIMATE DATA

Several sources of meteorological data exist for the Aspen and the Roaring Fork Watershed . These include weather stations in town at 7,945 ft (2,422 m), at the water treatment plant in the city of Aspen (elevation 8.163 ft [2,484 m]); several weather stations on the four ski areas: Aspen Mountain, Snowmass, Buttermilk, and Aspen Highlands; and a USGS SNOTEL site located at Independence Pass (elevation 10,600 ft [3,231 m]; http://www.wcc.nrcs.usda.gov/snotel/snotel.pl?sitenum = 542&state = co). Each of the climate data sources have unique applicability and reliability issues that needed to be addressed before any analysis could be conducted.

From conversations with ski area mountain managers, snow scientists, and professionals familiar with the available climate data, we determined that Aspen Mountain had the longest-term, and most reliable dataset. Data from the weather station at the top of Aspen Mountain (elevation 11,008 ft [3,355 m]) is available as far back as 1968, and is continuous through the current year, but measurements are only taken during the winter months when the ski area is operating (mid-November through mid-April). The modeling effort required full-year datasets to drive the models, forcing us to use data from the water treatment plant (elevation 8,148 ft [2,484 m]) or Independence Pass (10,600 ft [3,231 m]). Both locations have full-year records. Independence Pass was the closest, with the most reliable, complete, and representative data available, and was therefore selected as a surrogate for conditions at the upper part of Aspen Mountain. We used data from the Aspen weather station (2 locations) from the same timeframe from which we had Aspen Mountain data (1968-2005) to estimate conditions at the bottom of Aspen Mountain.[13]

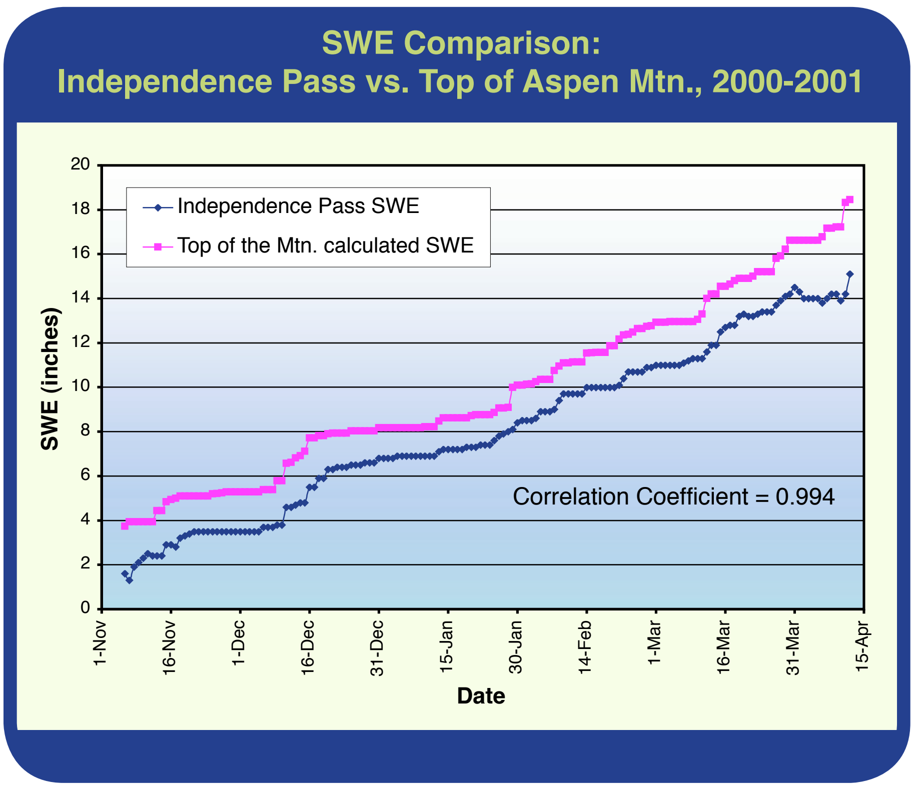


FIGURE 3.3: **Comparison of cumulative snow water equivalent (SWE) between Independence Pass and the top of Aspen Mountain for 2000-2001.**

Since we relied on Independence Pass measurements to predict ski area conditions, it was necessary to establish the relationship between the two locations. First, we needed to adjust the temperatures measured at Independence Pass for the slightly different elevation at Aspen Mountain.[14]

Second, a relationship between snowfall amounts between Independence Pass and Aspen Mountain needed to be determined. This comparison could only be done for the winter months when snowfall amounts from both locations were available. Although there were observed differences in daily snowfall amounts (in terms of snow water equivalent, SWE), cumulative snowfall totals correlated very well (Figure 3.3), with Aspen Mountain having approximately 6% greater precipitation totals than those at Independence Pass. We simply scaled daily measurements from Independence Pass by 6% to estimate precipitation amounts on Aspen Mountain.

3.4 SELECTION OF A REPRESENTATIVE YEAR

As indicated above, SRM requires estimates of snow covered area (SCA), on daily time intervals, for the selected timeframe as a data input. These estimates require remote sensing imagery. For the scale of our modeled basin (364 mi² [942 km²]), we selected high resolution Landsat and ASTER images because they provide more accurate estimates of SCA than courser scale images such as MODIS. The problem with using high resolution images is that they are expensive to buy which limits the number of images we were able to use in the SCA time series. So we chose a representative year that was reasonably consistent with historical averages.

After examining the historical data, and the availability of high-resolution images during the winter months, we chose the 2000-2001 season as our representative year. We demonstrated that the 2000-2001 winter season, defined as October 1,

13. Aspen weather data goes back to 1914; however, the station has been moved several times. We have only used data from 1968-2005 for this study. During the 1960's and 1970's the Aspen weather station was at 6th and Hopkins in Aspen at 7,945 ft and was moved to the water treatment plant at the end of 1979

14. We determined that the temperature lapse rate for the watershed to be 0.65°C/100m. This lapse rate was shown to be appropriate for the Aspen area by extrapolating water treatment plant temperatures to Independence Pass.

2000 through April 1, 2001, is reasonably consistent with historical averages (where the historical average is taken over the 1968-2005 time span). Figure 3.4 illustrates that the base depth at the top of Aspen Mountain for the 2000-2001 season is representative of the historical average. The dry and wet years of 2001-2002 and 1994-1995 are also displayed to provide some perspective.

3.5 REMOTE SENSING FOR SCA ESTIMATES

Snow cover was estimated from satellite imagery. Four Landsat (ETM+) scenes from 2001 (February 3, April 9, May 11, and June 6) and two scenes from the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) in 2000 (September 30 and December 1) were used to derive snow covered area for the winter season. The output for each date was then combined with digital topography to derive estimates of snow covered area by elevation band. Appendix F provides additional details on the remote sensing and GIS methods used.

Linear interpolation between estimated SCA values was employed to generate the required daily SCA time series.

3.6 SRM SET-UP AND MODEL RUNS

We first ran SRM to simulate runoff patterns for the 2001 water year to qualitatively calibrate the model parameters to accurately represent snowmelt and runoff conditions in the Roaring Fork watershed. A quantitative calibration would have required natural streamflow in the Roaring Fork at the Woody Creek confluence for the 2001 water year. However, these data were not available since stream gages represent actual observed streamflows, which differs from natural streamflows due to diversions, reservoirs, withdrawals, etc. A qualitative comparison to measured streamflow at the Glenwood gaging station demonstrated that the modeled timing of peak flows match with measured values, and the magnitude of flow was consistent with volumes observed near the Woody Creek confluence in past years. Once we determined SRM modeled historical conditions reasonably well, we modeled future climate change scenarios by scaling observed temperature and precipitation records

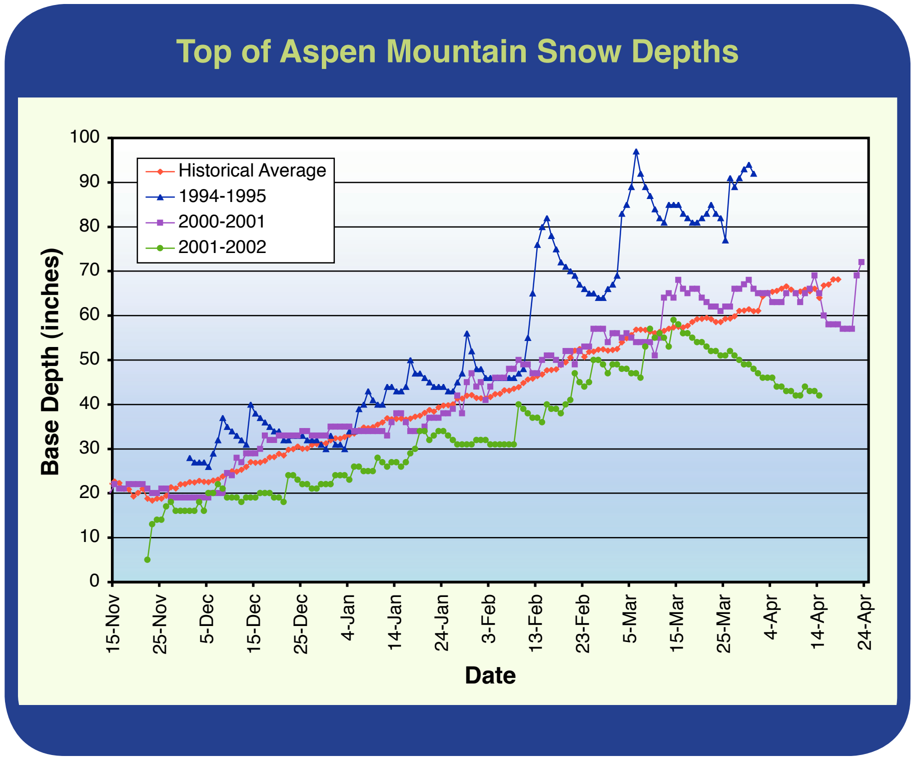


FIGURE 3.4: **Snow depths measured at the top of Aspen Mountain.** The historical average is taken from 1968 to 2005. The 2000-2001 season is representative of the historical average.

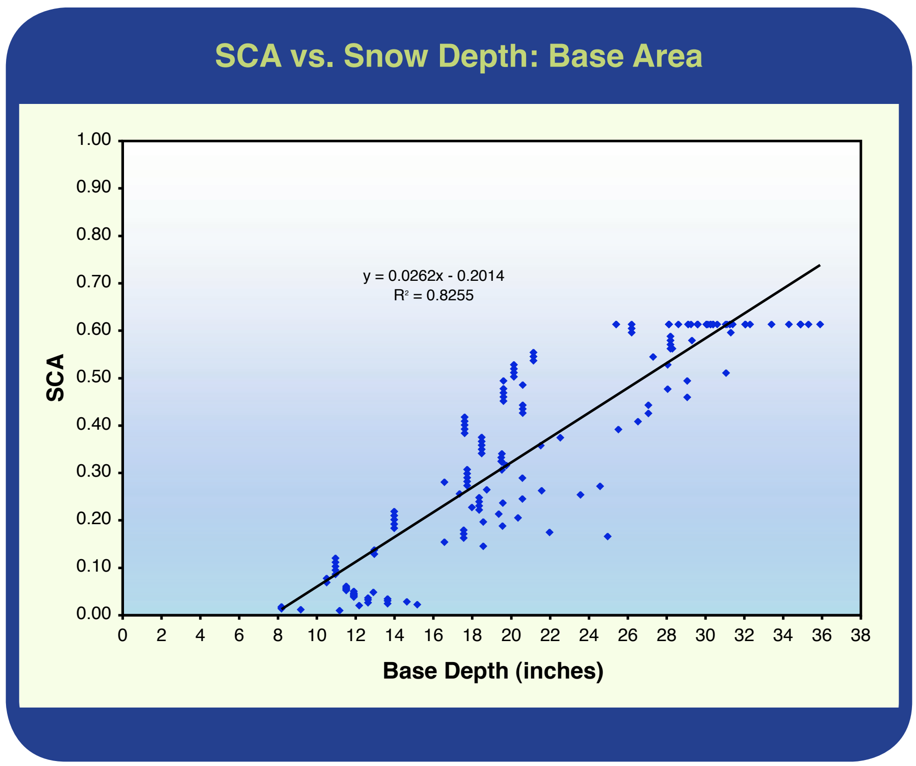


FIGURE 3.5: **Example of snow covered area (SCA) vs. snow depth relationship for zone 2 (8300-9300 ft.) of Aspen Mountain for the 2000-2001 season.**

by the predicted changes, unique to each scenario. We applied the monthly changes in temperature and precipitation from the climate scenarios derived from monthly GCM output to each day of the month in the daily data series for 2001. SRM output generated estimated SCA depletion curves from the winter end date (defined as March 1) to the end of the water year (September 30).

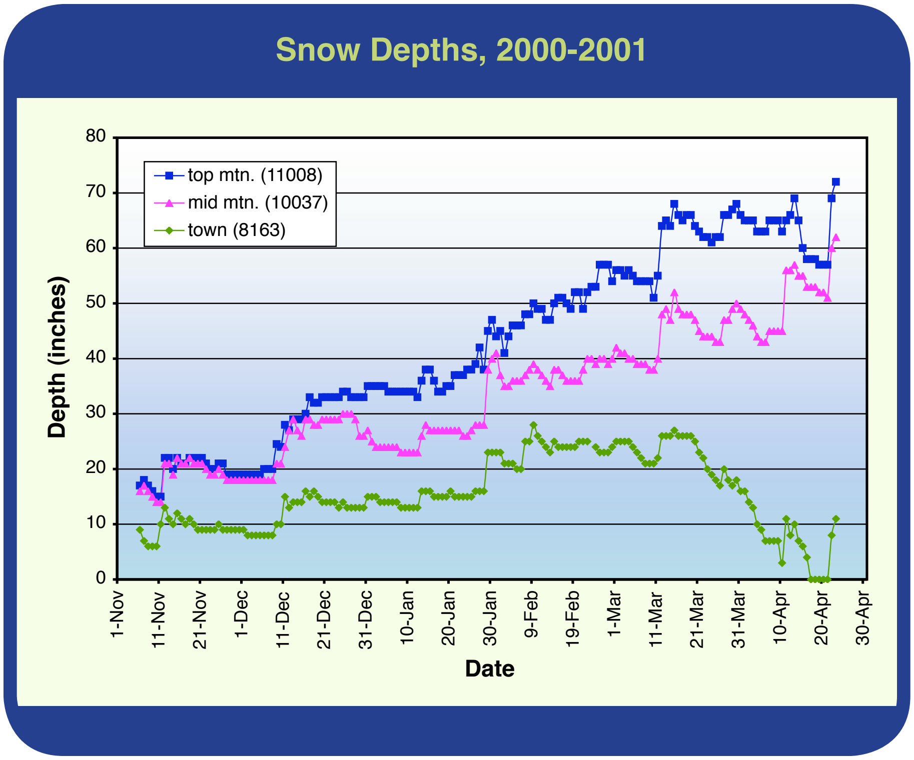


FIGURE 3.6: **Measured snow depths at the water treatment plant, mid and top of Aspen Mountain.** City of Aspen elevation is 7908 ft. The elevation of the Aspen weather station at the water treatment plant is 8163 ft.

SRM accounts for winter precipitation and stores any precipitation event recognized as snow, thereby calculating the maximum snow on store on the defined winter end date. Beyond the winter end date, SRM will model the melting process and the subsequent depletion of SCA. It does not, however, account for the rate and spatial distribution of snowpack buildup during the fall and early winter months. Since snowpack buildup is dictated by temperature and precipitation, we modeled this process in a spreadsheet we developed as an addition to SRM. Estimated changes in temperature were applied to observed historical records to determine the dates at which snow began accumulating, and SCA rates of change were scaled by the predicted changes in precipitation.

Snow depth was estimated by analyzing the relationship between SCA and snow depth for each elevation zone. By plotting SCA versus snow depth, and then conducting a simple linear regression analysis, we determined snow depths, based on measured SCA values (see Figure 3.5). The linear regression line represents the most likely snow depth values, but it must be noted that there is a scattered range of possible snow depths for any given SCA values, as shown in Figure 3.6.

We report the most likely snow depth value. The estimated snow depths were qualitatively compared to measured snow depths to ensure the SCA versus snow depth relationship represented the historically observed relationship reasonably well. This process required a snow depth time series for each elevation zone. Actual measured snow depth data were only available at the top of Aspen Mountain (11,008 ft [3,355 m]), the mid-mountain station (10,037 ft [3,059 m]), and at the water treatment plant near the base area elevation (8,148 ft [2,484 m]; Figure 3.6). These locations represent elevation zones 4, 3, and 2, respectively. To generate a snow depth time series for the other elevation zones, we employed linear interpolation between the three measured datasets. Since the relationship between the three measured datasets varied with date, a separate linear interpolation was conducted for each week throughout the winter.

We ran SRM using the methodology described above to predict snow pack characteristics for various future climate scenarios in the 2030's and in 2100. We added temperature changes in each scenario to those in the base year. Precipitation changes were added to one (e.g., a 15% increase becomes 1.15; a 5% decrease becomes .95) and multiplied by precipitation in the base year.

3.7 SRM MODELING RESULTS

The SRM modeling results for the 2030's and by the end of the century will be reported separately to distinguish between near-term and long-term future projections. A discussion of a critical threshold for opening, identified by ski area managers, follows.

3.7.1 THE 2030'S

The start of snow accumulation is defined as the date when precipitation not only falls as snow rather than rain, but also implies that snow remains on the ground and does not melt off immediately. This is termed the beginning of snowpack buildup. The start of snowpack buildup at the base area of Aspen Mountain begins approximately 1 week later in climate scenarios for 2030, as compared to the historical start date of November 8. This condition allows for some snowpack buildup to occur before Thanksgiving, and provides 2 weeks of conditions suitable for snowmaking. Snow melt at the base area initiates 4 to 5 days earlier than the historical melt initiation date of March 26, implying that skiable snow will exist at the base area throughout the spring break season in 2030. The modeled SCA results at Aspen Mountain's base area for 2030 are illustrated in Figure 3.7. The A1B_AVG and A1B_DRY scenarios, characterized by moderate warming and reduced winter precipitation, result in reduced maximum snow depths, and more rapid melting. The A1B_WET and SDSM scenarios, characterized by moderate warming and increased precipitation, illustrate that a 15% increase in winter precipitation can compensate for an approximate 2.7°F (1.5°C) winter warming, resulting in no significant change from current conditions.

There appears to be a larger impact of scenarios at the top of mountain (Figure 3.8). During the month of October, precipitation at the base area historically came mostly as rain as opposed to snow. The base area therefore did not historically rely on October snowfall for snowpack buildup. This is not the case at the top of the mountain. The top of the mountain historically received October precipitation in the form of snow, and thus snow depths are substantially affected if October precipitation arrives as rain, causing a deficit in snow depths (Figure 3.9). The A1B_WET and SDSM scenarios eventually reach the historical maximums because of the increased winter precipitation. In the A1B_AVG and A1B_DRY scenarios, winter precipitation either remains near current levels or shows a reduction. This, combined with the moderate warming, causes maximum snow depths to fall short of historic maximums. Although it may seem counter-intuitive, the A1B_WET scenario actually results in smaller snow depths than the average or dry scenarios by Thanksgiving. This is because the wet scenario, albeit wetter annually, has a drier and slightly warmer October than the other scenarios.

This October deficit pushes back snowpack accumulation at the top of the mountain 1

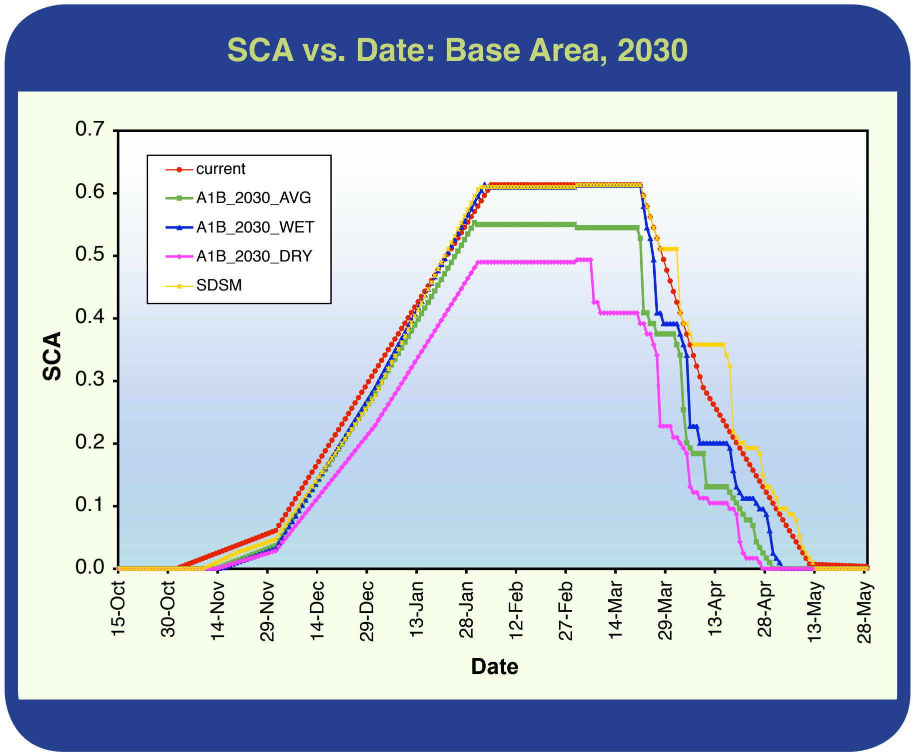


FIGURE 3.7: **Modeled snow covered area (SCA) time series for zone 2 (8300-9300 ft.) of Aspen Mountain by 2030.** Shown are the wettest, driest, and average of the five climate model projections for the A1B (medium emissions) scenario, compared to the current average. Also shown are results from statistical downscaling from HadCM3 (SDSM) under the B2 (a lower emissions) scenario. Both the A1B_AVG and A1B_DRY scenarios are characterized by reduced winter precipitation, while the A1B_WET and SDSM scenarios are characterized by increased precipitation. Dates are approximate for a typical snow season by 2030. SCA was modeled by scaling observed temperature and precipitation records by the changes projected by the four scenarios. The monthly changes in temperature and precipitation from the climate scenarios were applied to each day of the month in the daily data series for 2001.

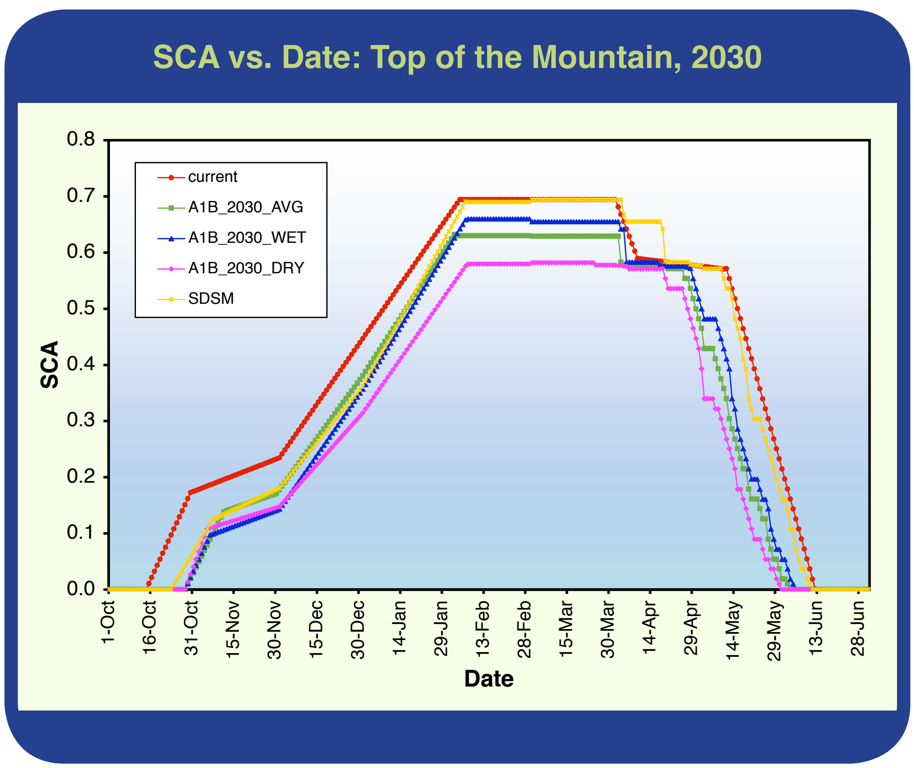


FIGURE 3.8: **Modeled snow covered area (SCA) time series for zone 4 (10,300-11,300 ft.) of Aspen Mountain by 2030.** Dates are approximate for a typical snow season by 2030.

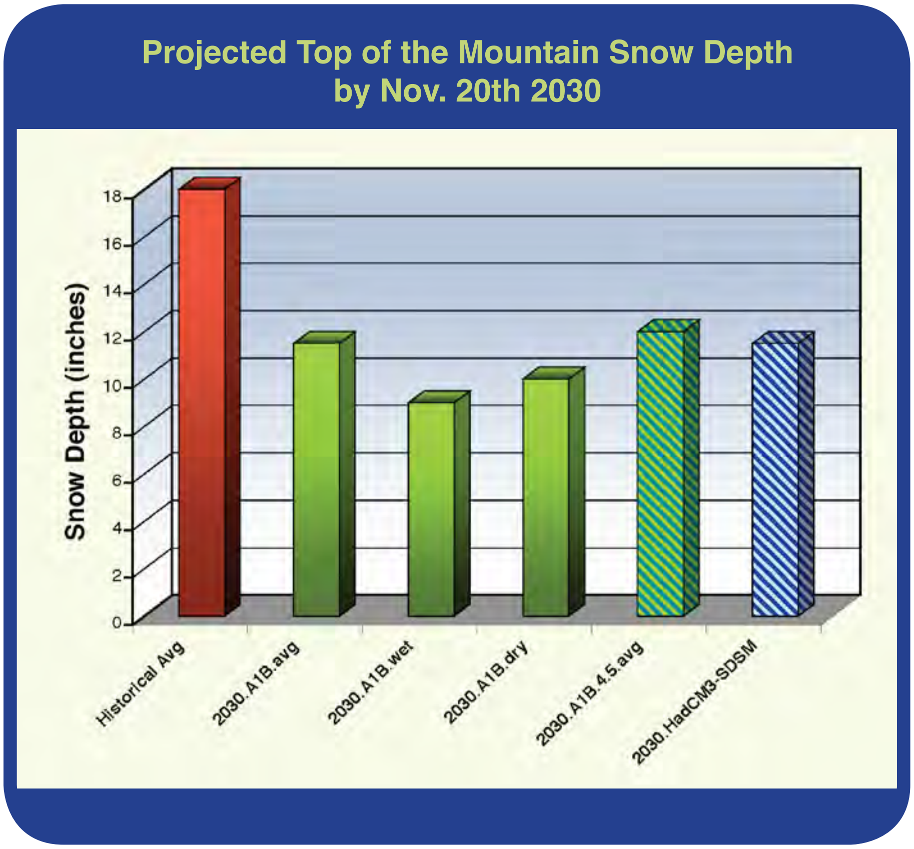


FIGURE 3.9: **Projected snow depths at the top of Aspen Mountain by November 20th, 2030.** Shown from left to right are the historical average, the average, wettest, and driest of the five climate model projections for the A1B (medium emissions) scenario (under 5.4ºF [3ºC] sensitivity), the average of the five climate models for A1B under 8.1ºF, or 4.5ºC, sensitivity, and the statistical downscaling results from HadCMS for the B2 (a lower) scenario (under 5.4ºF [3ºC] sensitivity).

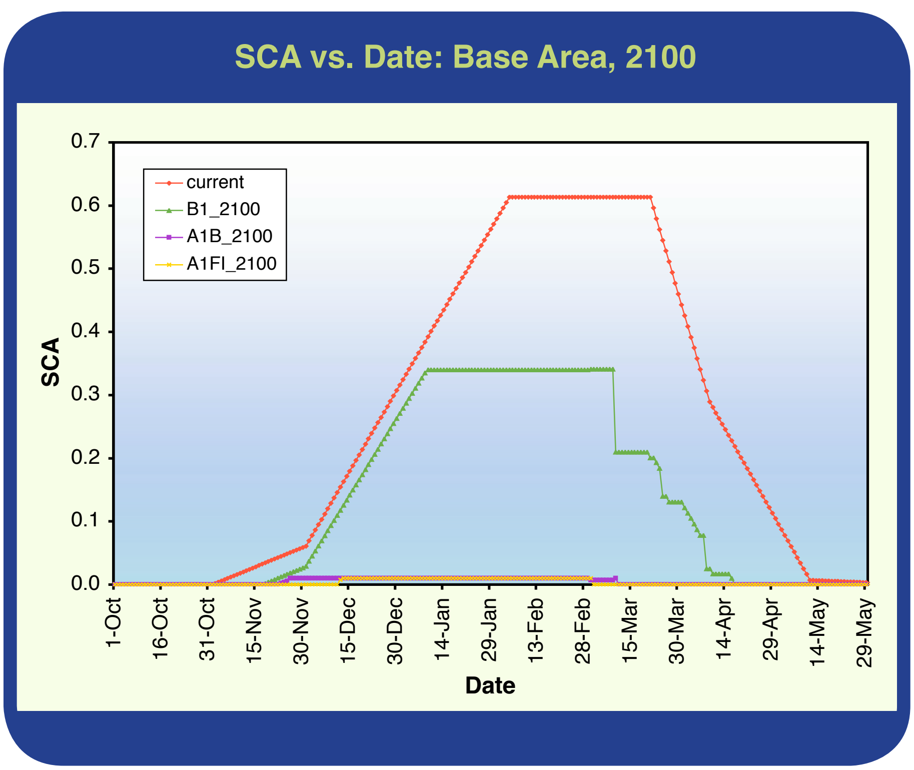


FIGURE 3.10: **Modeled snow covered area (SCA) time series for zone 2 (8300-9300 ft.) of Aspen Mountain by 2100.** Shown are projections for the low (B1), medium (A1B) and high (A1FI) emissions scenarios. Dates are approximate for a typical snow season by 2100.

to 2 weeks by 2030, and is the case in all modeled future climate scenarios for 2030. As the A1B_2030_WET scenario illustrates, this deficit cannot be made up, even with a 15% increase in winter precipitation. Modeled results also indicate that a seasonal snowpack is unlikely to persist below the elevation of approximately 7,500 ft (2,286 m).

3.7.2 By 2100

By 2100 the base area of Aspen Mountain has essentially lost a skiable snowpack, with the exception of the lowest greenhouse gas concentrations B1 model average scenario (Figure 3.10). There is virtually no snow cover under the A1B and A1FI model average scenarios. In the B1 scenario, the snow depths at the base area are substantially reduced, but not completely obliterated.

The start of snowpack buildup at the base area of Aspen Mountain begins anywhere from 1.5 to 4.5 weeks later in future climate scenarios for 2100, as compared to the historical start date of November 8. Snowmelt at the base area begins 2.5 to 5 weeks earlier than the historical melt initiation date of March 26th. As stated above, skiable snow will only exist at the base area under the B1 model average scenario conditions. Figure 3.11 illustrates how significantly base area snow depths are affected by 2100. It should be noted that the very low snow depths for the A1B and A1FI scenarios reach their winter maximum by December 20, and begin melting by early February. This is a substantial departure from historical patterns, where maximum snow depth is not usually reached until March.

The conditions at the mid-mountain elevations (9,300-10,300 ft [2,835-3,139 m]) show much less sensitivity to the A1B and B1 scenarios than the base area, but substantial sensitivity to the A1FI scenario. The cooler temperatures at this higher elevation insulate the snowpack from potential warming enough to maintain a seasonal snowpack in all but the A1FI high emissions scenario (Figure 3.12). The snow deficit caused by October precipitation received as rain is never made up, as indicated by maximum SCA values below the historical average values.

The critical elevation line where seasonal snowpacks are obliterated has moved from approximately 7,500 ft (2,286 m) in 2030 to approximately 9,300 ft (2,835m) for the A1B and B1 scenarios, and up to 10,300 ft (3,139 m) for the A1FI scenario. These results imply that skiable snow would exist from the mid-mountain and above for the A1B and B1 scenarios, but not for the A1FI scenario. Skiable snow would exist at the top of Aspen Mountain for all the scenarios, although snow depths would see a significant reduction (Figure 3.13).

3.7.3 Top of the Mountain Snow Depth Critical Threshold

Aspen Mountain ski area operations managers indicated that it is important to have a snow depth of 20 inches (5.08 cm) at the top of the mountain to open the ski area, ideally by Thanksgiving (see Chapter 5). This is primarily because snowmaking is not currently an option at the top of the mountain, and natural snowfall cannot be supplemented. Figure 3.14 illustrates the date at which this critical 20-inch snow depth condition is met in all the future run climate scenarios.

The 20-inch snow depth condition is not met by Thanksgiving in any of the future climate scenarios. The loss of October snow has a substantial impact on early season snow accumulation. If a 20-inch snow depth at the top of the mountain is a condition that must be met to open the ski area, the opening date could potentially get pushed back 1.5 to 2.5 weeks.

3.8 SNTHERM Model Run and Results

We modeled snowpack properties for both current (1980-2000) and the future (2020-2040) climate scenario generated by the downscaled PCM/RCM to assess the potential impacts of global climate change on snowpack characteristics. The objectives were to provide a more detailed analysis

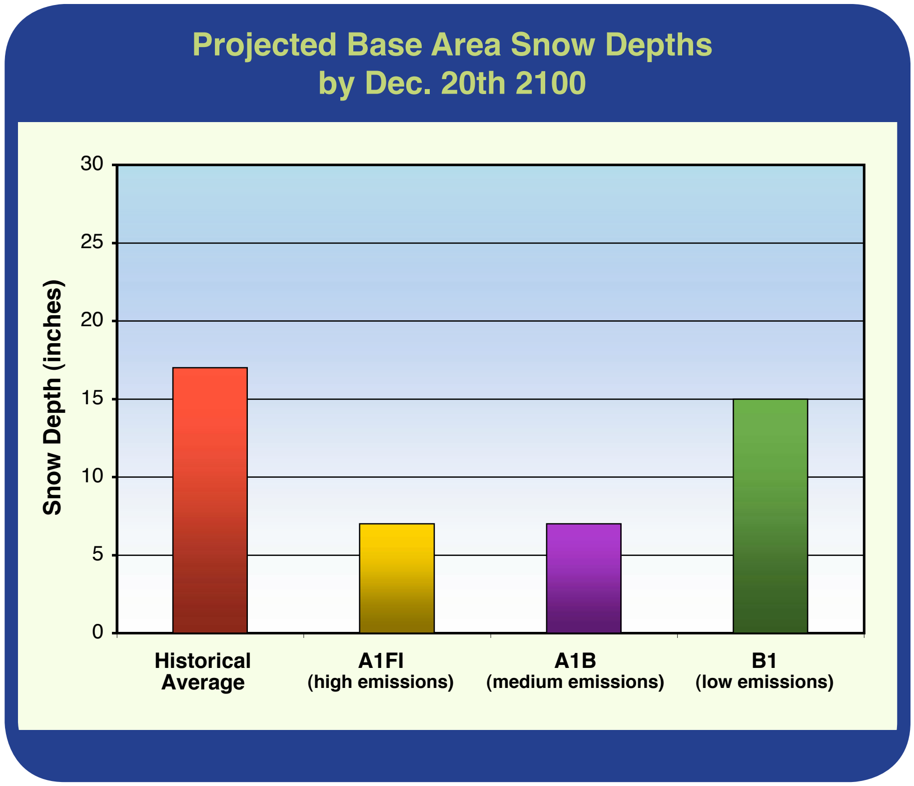


FIGURE 3.11: **Projected snow depths at the base area of Aspen Mountain by December 20th, 2100.** Shown are projections for the low (B1), medium (A1B) and high (A1FI) emissions scenarios, compared to the historical average.

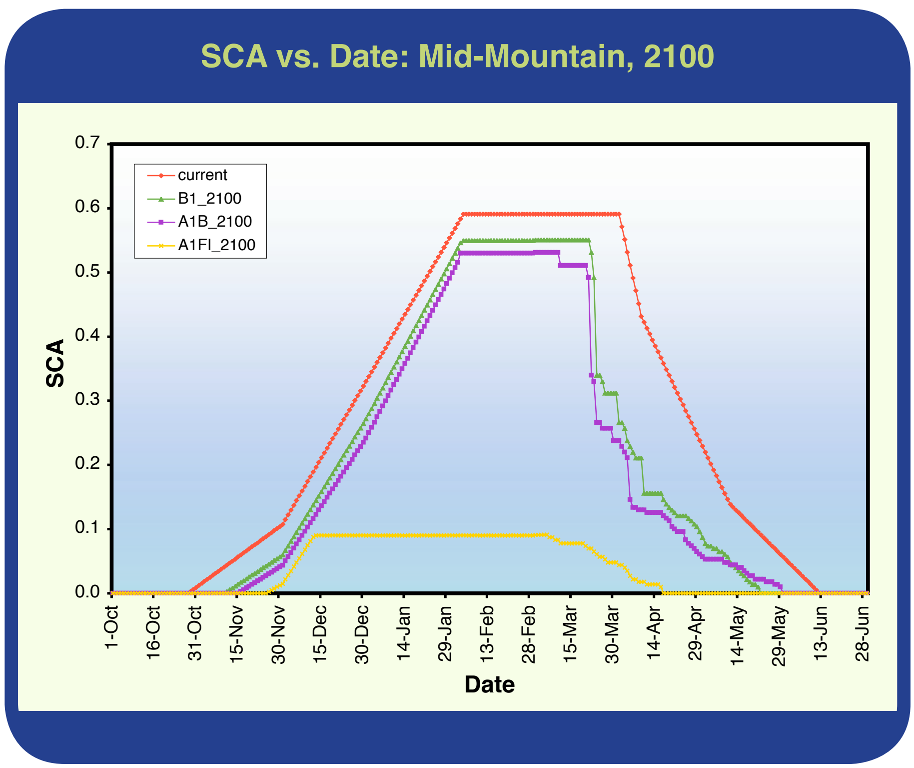


FIGURE 3.12: **Modeled snow covered area (SCA) time series for zone 3 (9300-10,300 ft.) of Aspen Mountain by 2100.** Shown are projections for the low (B1), medium (A1B) and high (A1FI) emissions scenarios. Dates are approximate for a typical snow season by 2100. SCA was modeled by scaling observed temperature and precipitation records by the changes projected by the three scenarios. The monthly changes in temperature and precipitation from the climate scenarios were applied to each day of the month in the daily data series for 2001.

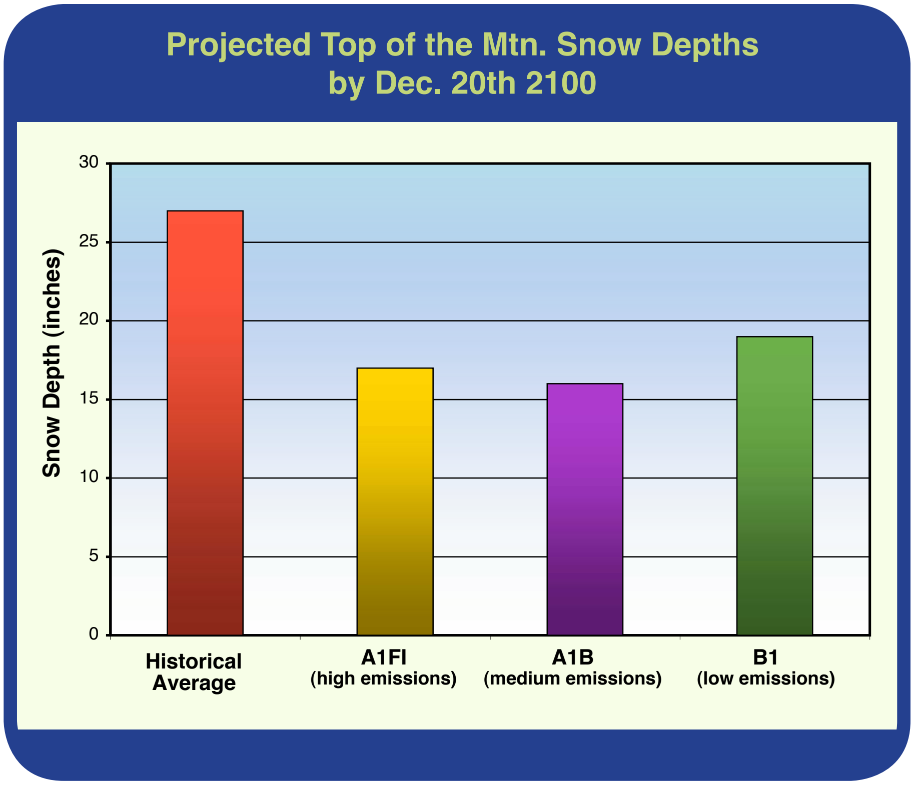


FIGURE 3.13: **Projected snow depths at the top of Aspen Mountain by December 20, 2100.** Shown are projections for the low (B1), medium (A1B) and high (A1FI) emissions scenarios, compared to the historical average.

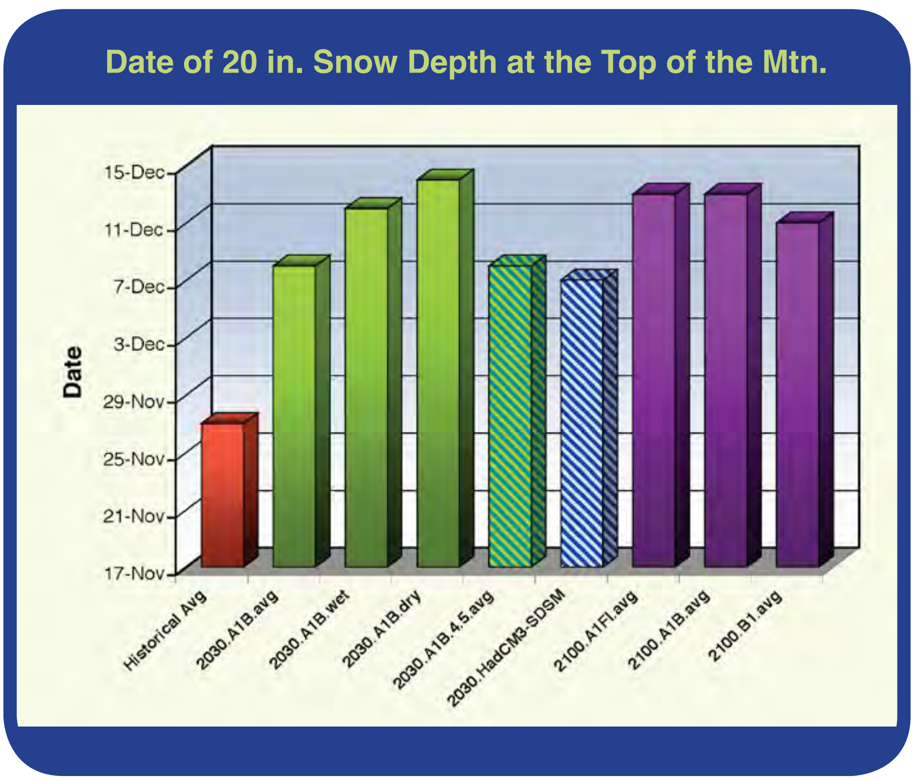


FIGURE 3.14: **Date when the critical threshold of a 20 inch snow depth at the top of Aspen Mountain is first achieved.** Shown from left to right are the historical average, the average, wettest, and driest of the five climate model projections for the A1B (medium emissions) scenario by 2030, the model average for A1B by 2030 under 8.1ºF, or 4.5ºC, sensitivity, the statistical downscaling results from HadCMS for the B2 (a lower) scenario by 2030, and the model average for A1FI, A1B, and B1 by 2100. All bars except SDSM are for 5.4ºF (3ºC) sensitivity. Dates are appoximate for a typical season by the years identified.

of the spatial variability of snowpack characteristics, address how snow quality in terms of density could change, and to provide an independent energy-balance approach to estimate snow depth in various landscape features. Only the PCM/RCM scenario was run because of the need for the full suite of meteorological variables.

The RCM model output contains the suite of variables required to drive the energy balance model. The modeled climate output then needed to be adjusted to each landscape type, as mentioned above. We accomplished this by using a discrete regions approach similar to that of Anderson (2005). It should be noted that the PCM/RCM scenario modeled a colder, wetter November than has been historically observed (see Chapter 2).

We estimated snow quality by calculating the bulk density in the top 4 inches of the snowpack, as this is the snow that people are actually skiing. We analyzed how snow quality differs with different elevations, aspects, and vegetative cover. The presence or absence of trees had very little effect on snow quality. In general, the lower elevations show an increased density from mid-winter to early March of approximately 3 to 18% (Figure 3.15). The mid-elevations are not as affected, but still show a substantial increase in density for February. There was very little difference in snow quality between northerly and southerly aspects, although the increased February density is still apparent. The decrease in estimated density in November is the result of the scenario's estimate of a decrease in November temperatures.

With the exception of the cooler and wetter November, snow depths at all elevations are estimated to be reduced. This reduction is more pronounced at lower elevations (Figure 3.16). In general, the lower elevations display a 12 to 15% reduction, and the higher elevations display a 6 to 7% reduction. As is the case with snow density, changes in aspect had very little affect on estimated snow depths.

3.9 SUMMARY

Using the climate change scenarios and SRM and SNTHERM models, we estimate that the date when snow starts to accumulate at the base is pushed back by approximately 1 week by 2030 and anywhere from 1.5 to 4.5 weeks by 2100. This is caused by an increase in air temperature. Earlier snowfall amounts in the warm-wet scenario melted in October and caused a lag in peak snow depth at the top of the mountain. In some scenarios, this causes the maximum snow depths to fall short of historical maximums. For mid-winter snows, a 15% increase in snowfall compensates for a 1.5°C (2.7°F) increase in air temperature such that there was little change in snow depth. Snow depth in 2030 during spring break showed a 7 to 25% decline in the base area, with small decreases near the top of the mountain. However, the onset of the spring avalanche cycle (melt initiation) started earlier by 4 to 5 days in all model runs. All model runs show skiable snow for all elevations on Aspen Mountain in 2030, but by 2100 this is only true for the B1 scenario. Results for the A1B scenario for 2100 indicate that a persistent snowpack will only exist for the upper two-thirds of the mountain. For the A1FI scenario, persistent snow coverage is confined to only the top third of the mountain. Snow depth goes to almost zero for the base area in 2100 under the A1B emission scenario. In the A1FI scenario, snow depth goes to near zero for the entire lower two-thirds of the mountain, with melt initiation beginning five weeks earlier. The effect is substantially reduced under the low emissions B1 scenario. In the A1B scenario, even in 2100 with a 7 to 9°F (4 to 5°C) increase in air temperature, there is little change in overall snow depth in the elevation bands from 9,500 feet (2,896 m) to the top of the mountain, compared to current levels. The level at which overall snow depth shows little change rises to 10,300 feet (3,139 m) under the high emissions A1FI scenario, which has a more substantial 11 to 12.5°F (6 to 7°C) ski season warming. In spite of the reduction in snowpack, snow quality has less than a 20% increase in the density of the top few inches of snow by 2030, which in our judgment, does not substantially reduce the quality of the snow. By 2100 densities could be substantially higher.

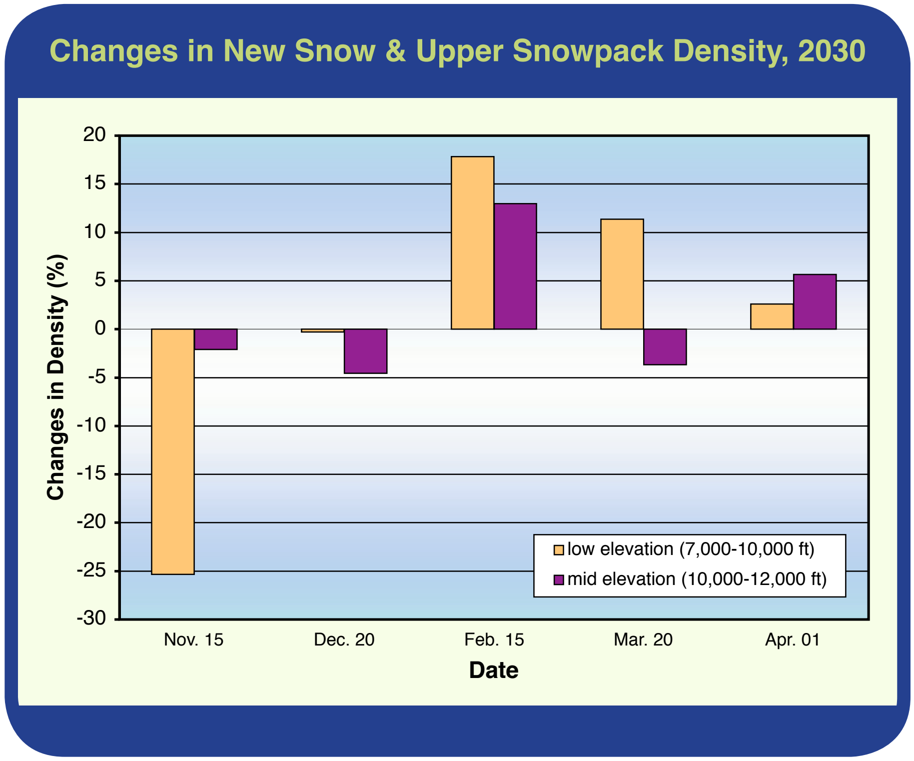


FIGURE 3.15: **Changes in snow quality by elevation by 2030.** Dates are approximate for a typical snow season by 2030.

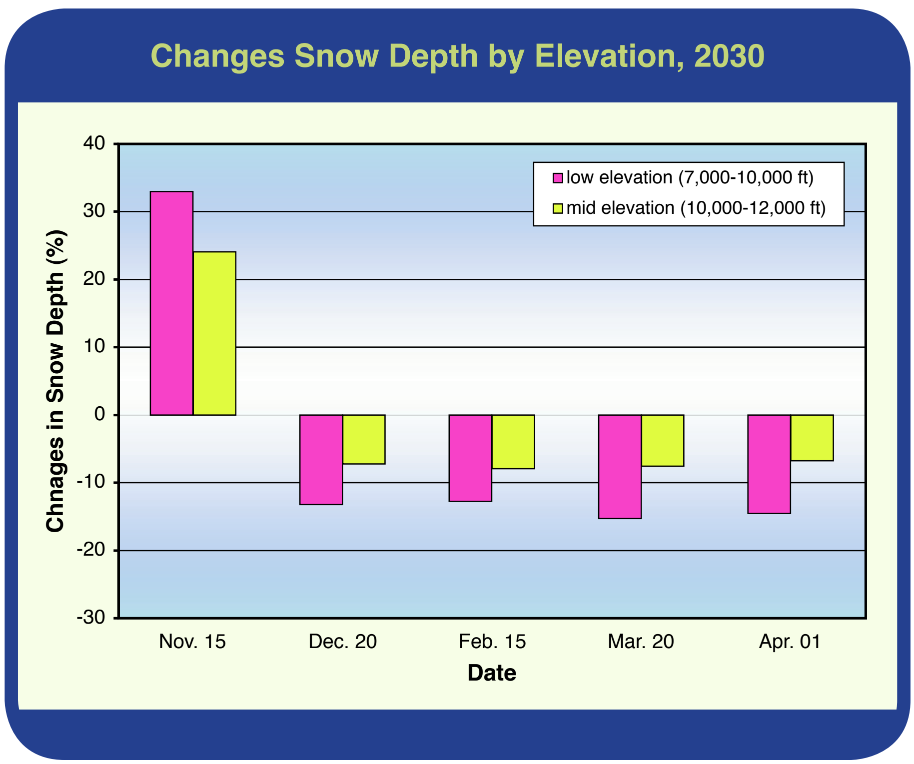


FIGURE 3.16: **Changes in snow depth by elevation by 2030.** Dates are approximate for a typical snow season by 2030.

4. POTENTIAL IMPACTS OF CLIMATE CHANGE ON ASPEN'S ECOLOGY

4.1 INTRODUCTION

Through the alterations to physical aspects of climate discussed in Chapters 2 and 3, climate change has the potential to affect the ecology of the Aspen area. Over time scales of decades to centuries, changes in temperature and precipitation can result in substantial changes in the makeup of plant and animal species found in the Roaring Fork Valley. Under conditions of a changing climate, forest biomass, wildfire patterns, and insect outbreaks can also change, potentially impacting ecosystem structure and function in the Aspen area.

The first part of this section discusses how future climate scenarios may affect vegetation types and carbon storage, fire risk, and risks of insect outbreaks. The second part of the chapter describes the local ecological communities and how they could be influenced by climate change.

4.2 CHANGES IN ECOSYSTEM PROCESSES

One approach to exploring the relationship between climate change and natural systems is to look at impacts on vegetation types in relation to different climate change scenarios. This section looks at modeled changes in vegetation types and associated shifts in carbon storage, wildlife, and insect outbreak regimes.

4.2.1 Changes in vegetation types and carbon storage

Vegetation models are important tools for evaluating how climate change might alter the size and distribution of different biomes, as well as the net growth or decline of an ecosystem (measured as changes in the storage of carbon). We used predictions made by a dynamic general vegetation model called MC1 (Bachelet et al., 2001) to evaluate potential large-scale shifts in vegetation processes in the Aspen area. MCI combines a biogeography model MAPSS (which estimates location of vegetation types) and a biogeochemical model (CENTURY),which estimates productivity and nutrient cycling. Thus, MC1 can be used to estimate changes in location and productivity of vegetation. MC1 assumes a moderate carbon fertilization effect (R. Neilson 2006, pers. comm., 15 June). This model has been used to predict effects of climate change on the distribution of major types of vegetation (biomes), carbon storage, and wildfire across North America, at a one-half degree (latitude and longitude) scale of resolution. MC1 is a type of model "specifically designed to dynamically simulate combined changes in vegetation distribution, vegetation growth and decline and changing disturbance regimes (fire) under rapid climate change" (Neilson et al., 2005).

We obtained modeled results for the 925 square mile (2,396 km^2) "grid cell" that includes Aspen (See Fig 2.7 & 4.1). We also examined general results for Colorado. It is important to keep in mind that the model was not designed specifically for the Aspen area, and a site-specific model might have yielded different results. In addition, since the model runs at a scale substantially larger than the Aspen area, the results do not differentiate between different elevations or climate zones within the Aspen area. MC1 assumes that there is only one biome in the grid cell containing Aspen, not the many biomes that are now found there. Nonetheless, analysis of MC1 results for the Aspen area and for Colorado allows for a general understanding of the possible outcomes of climate change, and for estimating ecological and human risks that could be addressed in adaptation planning. For example, it can tell us whether Aspen's climate will shift to be more suitable for vegetation that can tolerate more heat and drought than vegetation currently found in the area.

Vegetation model methods

The MC1 model was run using six different climate scenarios and two different fire management practices (current fire suppression practices and no fire suppression). The model does not specifically include other types of forest management, such as logging or selective thinning. The model runs were conducted as part of the Vulnerability and Impacts of North American Forests to Climate: Ecosystem Responses and Adaptation (VINCERA) project, which is designed to compare three different vegetation models running under six climate scenarios. The six climate scenarios are a combination of three different general circulation models (GCMs) using two different emissions scenarios.

The emissions scenarios, which were developed by the Intergovernmental Panel on Climate Change (IPCC) in its Special Report on Emissions Scenarios (SRES), are known as A2 and B2. These are different from the SRES scenarios used in the climate and snowpack parts of the study (Chapters 2 and 3). The A2 emissions scenario most closely resembles the A1FI scenario and B2 is closest to the A1B scenario used earlier in the report. (See Figure 1.5 for a comparison of the different SRES emission scenarios over the 21st century). In general, the A2 scenarios predict higher greenhouse gas (GHG) emissions over the next 100 years than the B2 scenarios (IPCC, 2000a). The GCMs include the following models: the Canadian Climate Centre CGCM2 model, the Hadley Centre HADCM3 model, and the Australia CSIRO-MK2 model; Table 4.1. Only output from the Hadley Centre model is used in the snowpack analysis. All of the climate scenarios predict 10.8 to 16.2°F (6 to 9°C) average temperature increases over the United States and Canada by 2100 (Neilson et al., 2005).

Comparison of Vegetation Biomes as Predicted by the MC1 Model

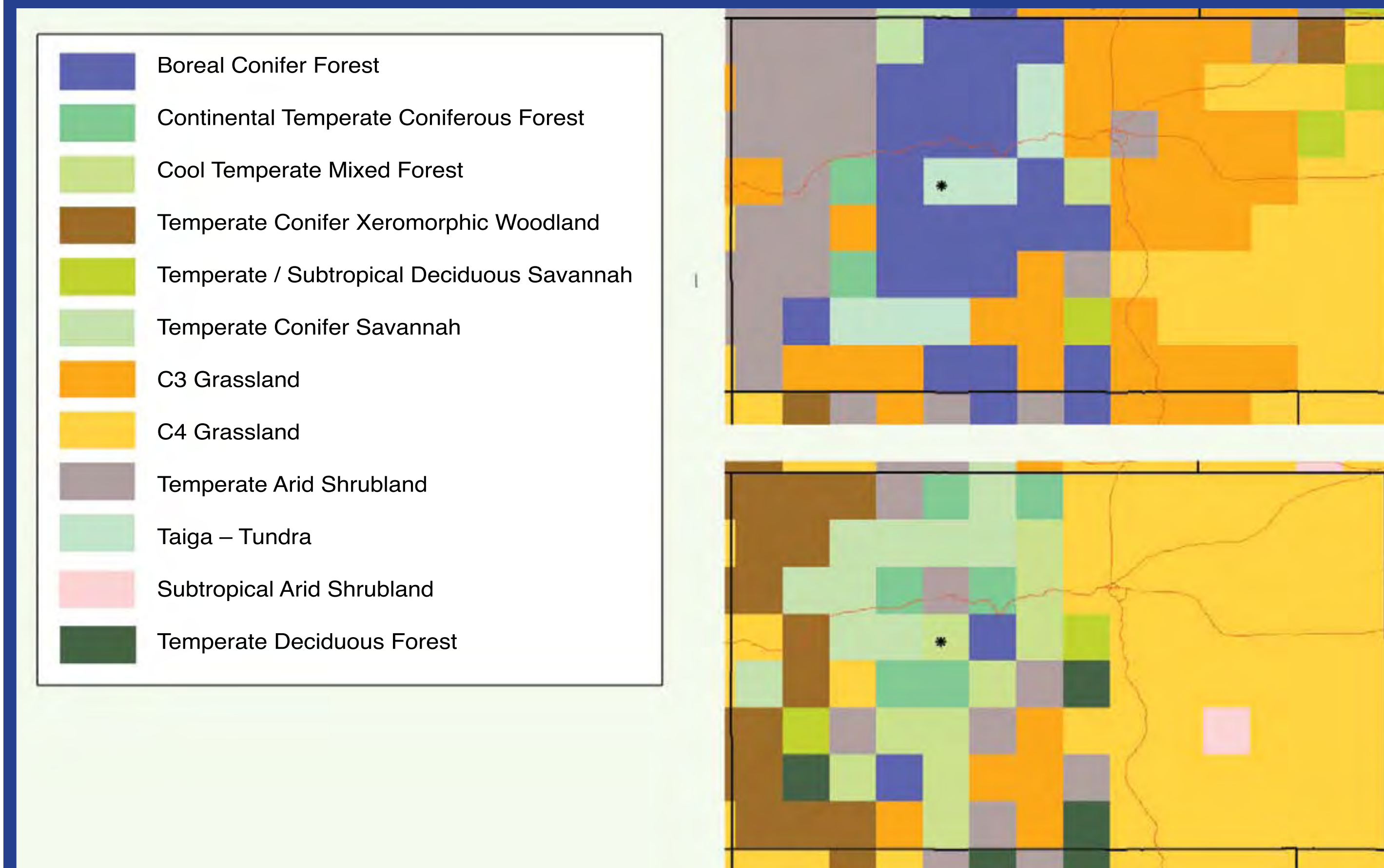


FIGURE 4.1: **Comparison of vegetation biomes as predicted by the MC1 model for climate conditions in 2000 (top panel) and for future climate conditions (bottom panel) in the late 21st century, using the HadCM3 climate model.** Area shown is 106.5-107°W and 39-39.5°N. The asterisk shows the location of Aspen, Colorado. Each colored square depicts the dominant biome for a 0.5° x 0.5° grid cell. (Source: MAPSS Team (Leader, Ron Neilson), VINCERA Project, USDA Forest Service)

Summary of Abbreviations for Climate Scenarios used for Forest Fire Modeling with MC1

Global Climate Model	Emissions Scenario A2 (higher emissions)	Emissions Scenario B2 (lower emissions)
Canadian Climate Centre	CGCM2a	CGCM2b
Hadley Centre	HADCM3a	HADCM3b
Australia	CSIRO-MK2a	CSIRO-MK2b

TABLE 4.1: **Summary of abbreviations for climate scenarios used for forest fire modeling with MC1.**

Changes in vegetation type

The MC1 vegetation model predicts the potential vegetation type (biome) for each half-degree by half-degree grid cell under current and future climate conditions. This means, for example, that the model does not include agricultural or urban land cover types. Furthermore, the model does not take into account different elevation zones or landscape heterogeneity within a grid cell. The model also assumes that vegetation type is in equilibrium with climate. This means that no lag time is required to shift from one vegetation type to another under conditions of changing climate. These simplifications (common to large-scale modeling efforts) mean that the best way to interpret the biome results is not as a future prediction of the actual vegetation type that will be present in a specific spot, but as an indication of how overall climatic conditions of temperature and precipitation may change to become suitable for different biomes.

Within Colorado (Figure 4.1), the MC1 simulation of climate conditions for 2000 predicts dominance by boreal conifer forest and taiga-tundra biomes in mountain areas. The taiga-tundra biome describes a transitional zone between boreal forest (taiga) and tundra (above tree line) conditions. Under future climate conditions at the end of the 21st century (using the HadCM3 model), the climate has shifted so that warmer vegetation types, including continental temperate coniferous forest and cool temperate forest, are estimated to predominate in mountain areas. Again, because the model does not simulate vegetation diversity within a grid cell, these results do not necessarily predict the disappearance of boreal conifer forest or arctic tundra. Instead, the model outcomes suggest that a grid cell that may have been dominated by boreal conifer forest or taiga-tundra under current climate conditions will instead be dominated by a forest typical of warmer regions, with perhaps boreal conifer forest or tundra occupying a smaller proportion of the total area. The MC1 simulation does not capture the complexity of the vegetation within the biomes. Instead, it is meant to be a rough prediction of the direction of change from one biome to another that is likely to be seen in our region.

For the Aspen area, the dominant vegetation type could shift from tiaga-tundra to boreal conifer forest by the 2020's.

For the grid cell that includes the Aspen area, all of the climate scenarios used in the VINCERA project estimated that the dominant vegetation type would shift from taiga-tundra to boreal conifer forest by the 2020's. After 2080, the three GCMs run with a high emission scenario estimated a shift to an even warmer vegetation type (continental temperate coniferous forest or cool temperate mixed forest), while the lower-emission scenarios estimated a continuation of boreal conifer forest as the dominant vegetation type.

Changes in biomass

The MC1 vegetation model also estimated vegetation biomass, measured as above-ground and below-ground biomass in units of grams of carbon per square meter. In a forested area, for example, an estimated increase in above-ground carbon, under future climate change conditions, indicated above-ground forest growth (either larger trees or higher tree density), while an estimated increase in below-ground carbon indicated that root growth is exceeding decomposition. Of course, there are tight interactions between carbon modeling results and fire scenarios.

The selection of fire scenarios (suppression or no suppression) is strongly correlated with changes in above-ground biomass. Under a fire suppression scenario, three of the models showed increases in vegetative carbon between 6% and 14% during the 21st century, while three of the models estimated slight decreases in vegetative carbon of 0.4% to 5%. For each GCM, the higher emissions scenario resulted in larger estimated increases in vegetative carbon compared to the lower emissions scenario (Figure 4.2, top).

Under scenarios of no fire suppression, all of the models estimated decreases in vegetative carbon, presumably because of the increase in fire frequency or size. The amount of net decreases for five of the six models range from 20% to 28%, while the Canadian Climate Centre Model, under the lower emissions scenario, estimated a net decrease of just 9% (Figure 4.2, bottom).

The different scenarios of future climate change have a smaller, but consistent effect on below-ground carbon compared to above-ground carbon. For the fire suppression scenarios, the estimated net change in below-ground carbon varies from a decrease of 3% to an increase of 7%. For the no suppression scenarios, the estimated net change in below-ground carbon varies from a decrease of 9% to an increase of 1%.

The models show a tight link between fire scenarios and above-ground biomass. Under scenarios of fire suppression, the models vary in their estimations from slight decreases to minor increases of less than 15% over 100 years. With frequent or large fires, above-ground biomass is estimated to decrease by as much as 28% by 2100. Assumptions about fire suppression result in widely varying future projections about biomass within these forests.

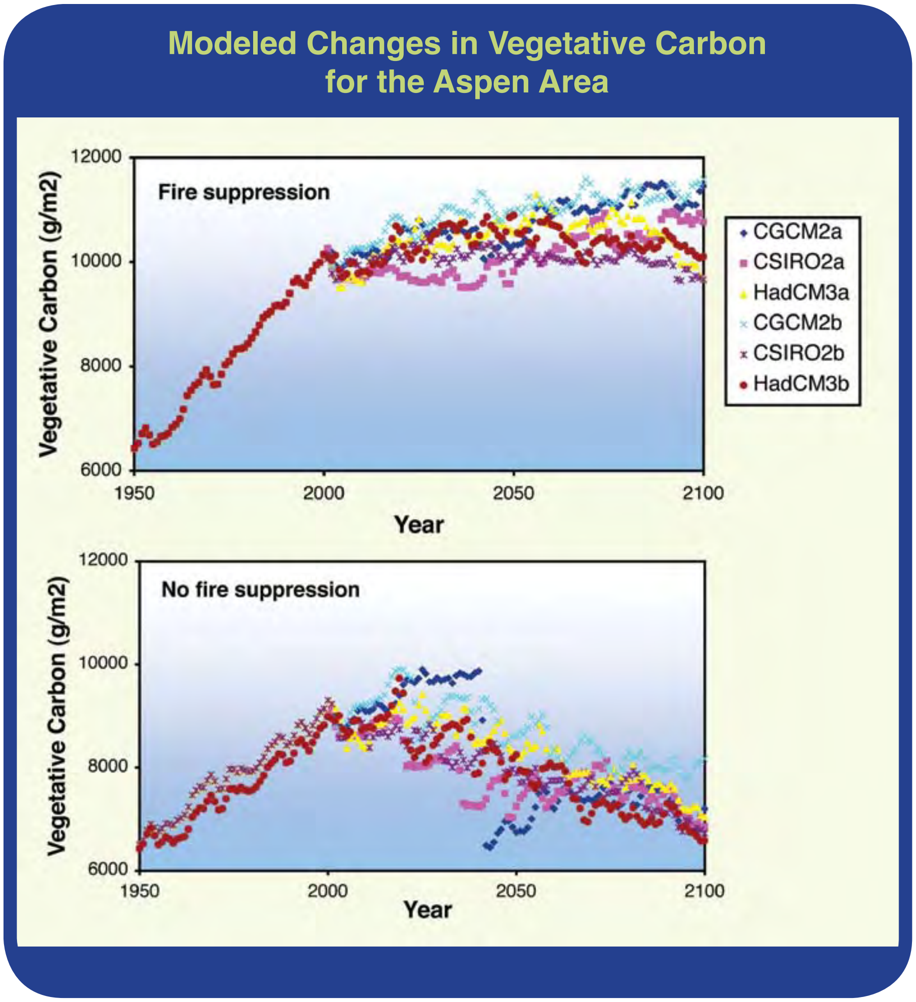


FIGURE 4.2: **Modeled changes in vegetative carbon for the Aspen area from 1950 to 2100, using the MC1 model.**

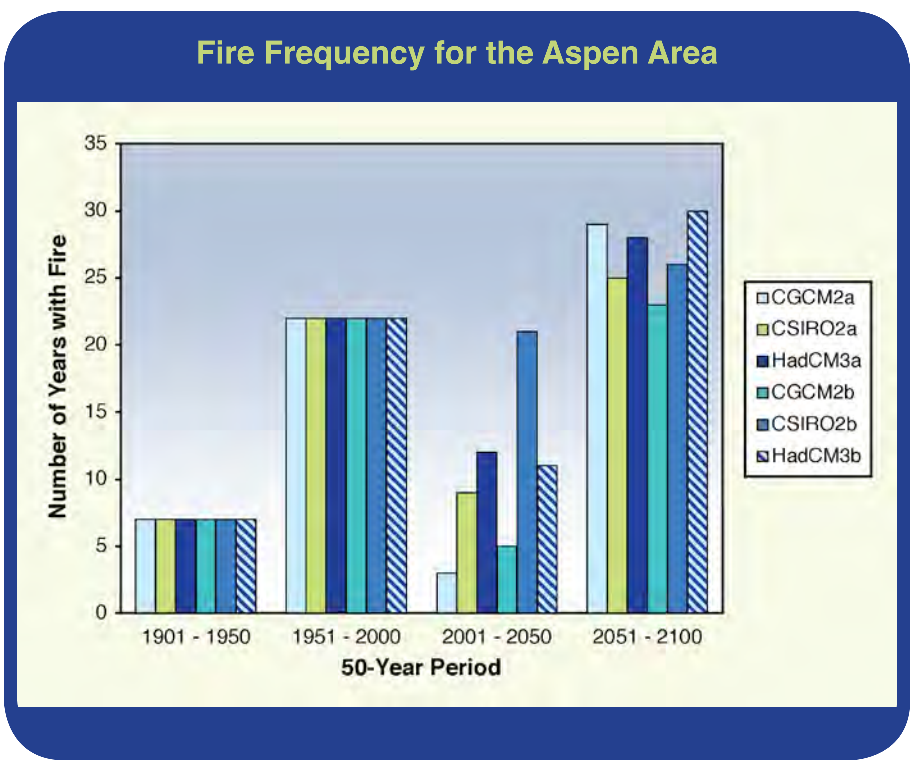


FIGURE 4.3: **Modeled fire frequency for the Aspen area from 1901 to 2100, using the MC1 model.** Different bars correspond to different climate scenarios; see text for details. Number of years is frequency within a 50-year period.

4.2.2 Changes in fire risk

Wildfire is an important process for maintaining healthy ecosystems in western forests such as the forest around Aspen in the Roaring Fork Valley. Decades of fire suppression have altered historical fire regimes so that fuel loads are higher and fire-return intervals are longer. In combination with the long-term detrimental effects of fire suppression, climate change has the potential to alter fire behavior, including changing fire frequency and fire size (McKenzie et al., 2004). Periodic drought and higher temperatures can lead to decreased fuel moisture, which increases fire frequency. Conditions that lead to increased vegetation growth, such as increased precipitation and longer growing seasons, can increase fire size because of increased fuel loading. Thus, paradoxically, both increased precipitation and decreased precipitation can result in fire risk increases. Climate change scenarios of increased precipitation in many years, interspersed with occasional severe droughts, substantially increase the probability of fire (Bachelet et al., 2001).

In addition, there are potential interactions between wildlife and insect outbreaks. In recent years, the Rocky Mountains have experienced increased impacts from insects and pathogens that can kill or damage trees. Insect outbreaks can lead to the increased chance of fire because dead needles stay on trees after they die and ignite more readily than living trees. Significant increases in fire frequency and fire size could have detrimental effects on ecological processes and sensitive species (e.g., McKenzie et al., 2004), as well as the quality of life in the Aspen area and a tourism economy. Wildfires have negative impacts on air quality (haze and smoke), and can present a risk to life and property.

Methods

Vegetation and fire models are important tools to evaluate how climate change might alter fire frequency and fire size. We used modeling results to determine how the size and frequency of fires in the Aspen area might change over the 21st century under different climate change scenarios. MC1 includes a mechanistic fire model that determines how much and how frequently fires burn, based on fuel loading and fuel moisture characteristics. This model has been used to estimate the effects of climate change on wildfires across North America, at a one-half degree (latitude and longitude) scale of resolution.

Results – Fire Frequency

In the Aspen area, the models estimate that fire frequency would eventually increase in the 21st century compared to the 20th century (Figure 4.3). This area is estimated to experience a period of relatively infrequent fire from 2001 to 2050 and then undergo a transition to a time of frequent fire, with fires occurring on average every other year. This corresponds to the general hypothesis of climate change causing "early greenup, later browndown" (Bachelet et al., 2001). Vegetation initially benefits from climate warming because of increased precipitation, a longer growing season, and higher water use efficiency in the presence of elevated carbon dioxide levels in the atmosphere. Over time, however, increasing temperature is predicted to lead to vegetation diebacks, because of drought, insect outbreaks, and fire (Neilson et al., 2005).

Across the different climate change scenarios, results are relatively consistent with all the climate scenarios projecting more fire during the second half of the 21st century compared to the first half of the 21st century (Figure 4.3). For the period 2051-2100, fire is estimated to occur in 23 to 30 years. For the period 2001-2050, estimates range from 3 to 21 years. There is no difference in estimated fire frequency between the "suppression" and "no suppression" scenarios for fire frequency. The suppression scenarios contain fire size once a fire starts, but do not affect the frequency of fire ignition.

Results – Fire Size

Assumptions about fire suppression make a difference with regard to the estimated size of fires. We examined average and maximum estimated fire sizes from the different model outputs. The average fire size is an estimate of the number of acres likely to burn in a given year with fire. Maximum fire size is an indication of catastrophic fire risk. Both of these indicators

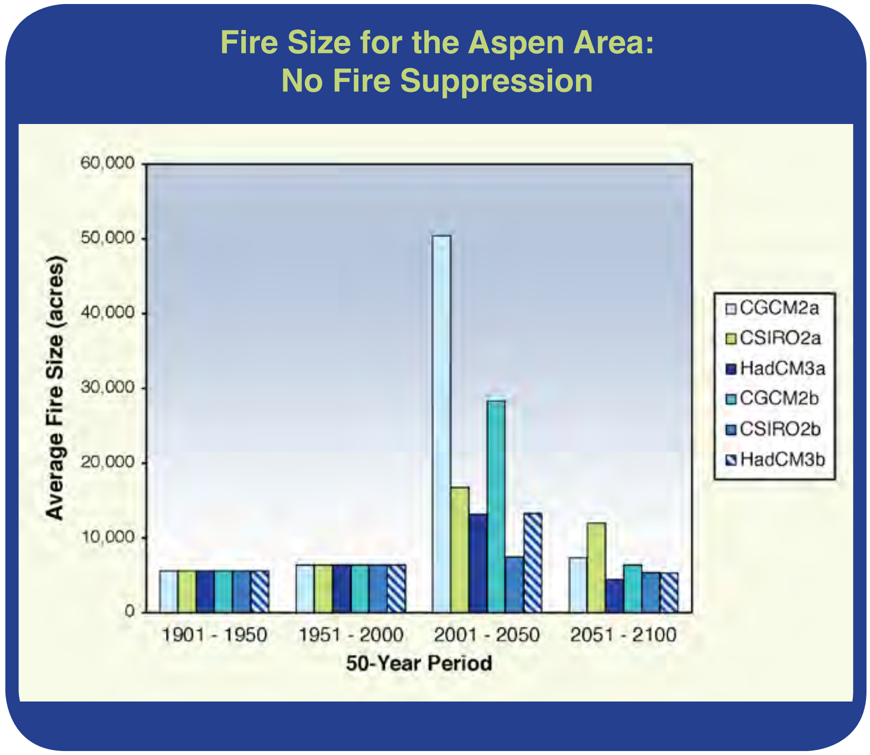


FIGURE 4.4: **Modeled fire size for the Aspen area from 1901 to 2100, using the MC1 model under a no fire suppression scenario.** Different bars correspond to different climate scenarios; see text for details. Average fire size for the period from 1901 to 1950 excludes a modeled fire event in 1934 of 225,000 acres that is not thought to correspond to an actual historical fire in the Aspen area.

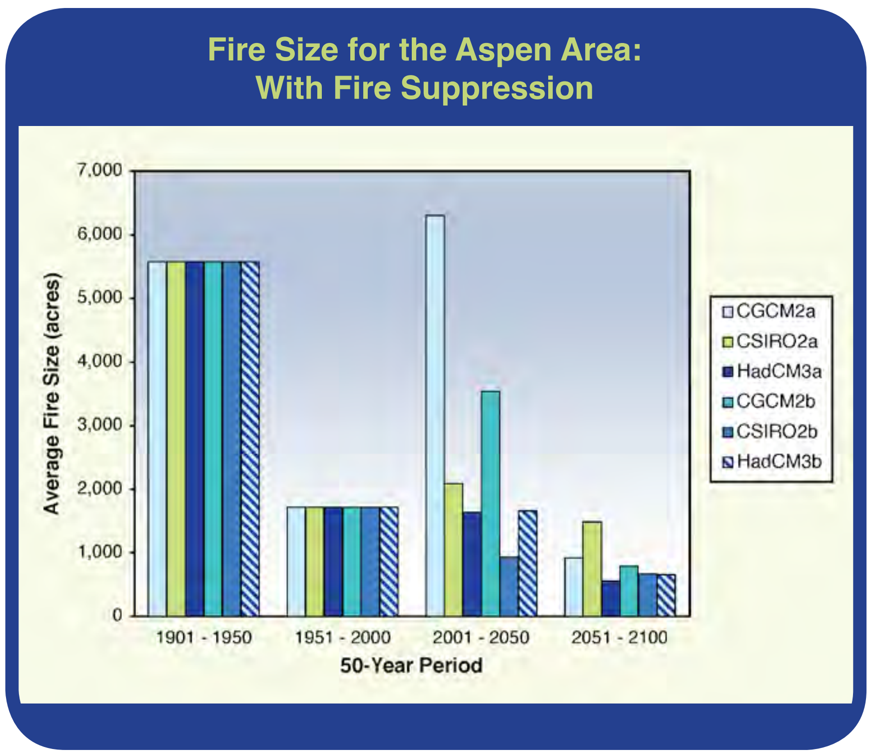


FIGURE 4.5: **Modeled fire size for the Aspen area from 1901 to 2100, using the MC1 model under a fire suppression scenario.** Different bars correspond to different climate scenarios; see text for details. Average fire size for the period from 1901 to 1950 excludes a modeled fire event in 1934 of 225,000 acres that is not thought to correspond to an actual historic fire in the Aspen area.

are helpful in estimating potential ecological and economic impacts of wildfire. Frequent large fires, for example, would be much more likely to have an economic impact on tourism than frequent small fires. All of the results described below for no suppression and fire suppression are rounded averages of the six different climate scenarios.

During the first half of the 21st century, the no suppression scenarios project the average fire size to be approximately three times larger than during the period from 1951 to 2000, while the fire suppression scenarios project the average fire size to be approximately 1.6 times larger than from 1951 to 2000. During the second half of the 21st century, both the no suppression and the fire suppression scenarios in the Aspen area estimate that the average fire size would be smaller than during the 20th century. These results are probably a consequence of the increase in fire frequency, with more frequent fires, fuel-loading decreases, and fire size decreases.

> The Aspen area may experience less frequent, larger fires during the first half of the 21st century, and more freqent, smaller fires during the second half of the century.

The model estimated substantial differences between the suppression and no suppression scenarios, with larger average and maximum fires under the no suppression scenarios. Average fire size during the entire 21st century is estimated to be approximately 14,000 acres (56.7 km^2) (2.4% of the modeled area) under the no suppression scenario, and 1,800 acres (7.3 km^2) (0.30% of modeled area) under the fire suppression scenario (Figures 4.4 and 4.5). The maximum estimated fire size during the 21st century was 130,000 acres (526 km^2) under the no suppression scenario, and 16,000 acres (64.7 km^2) under the suppression scenario (not shown).

Fire Risk Conclusions

These results suggest that under climate change, the Aspen area may first experience less frequent, larger fires during the first half of the 21st century, and then, during the second half of the century, experience more frequent, smaller fires compared to conditions during the 20th century. On average, fires are estimated to occur every other year in the Aspen area during the second half of the 21st century. These results do not exclude the possibility that severe, large fires could burn in the Aspen area under extreme conditions. Although these modeling results did not estimate an individual large fire event during the 21st century, the possibility of increased vegetative growth under climate change (resulting from a longer growing season and carbon dioxide fertilization) combined with the periodic risk of severe drought, means that severe fire is always a possibility for western forest ecosystems (McKenzie et al., 2004).

There are also complex interactions between climate change, fire suppression, and forest management. Forest management actions such as controlled burns or logging that decrease fuel loading will tend to decrease fire size, while fire suppression activities that increase fuel loading will tend to increase fire size. The particular effects of climate change on wildfire behavior in the Aspen area are likely to depend largely on forest and fire management policies in the different vegetation zones. For example, designated Wilderness Areas around the Roaring Fork Valley cannot be managed with logging and controlled burns, so these areas are more likely to follow the trajectory of a "no fire suppression" area. Ultimately, above-ground biomass is estimated to eventually decline; how soon this would happen appears to depend on whether fire suppression policies are continued or are abandoned.

4.2.3 Changes in Risk of Insect Outbreaks

Native insect and pathogen disturbances can be part of the natural cycle of forest growth and regeneration. Certain forest types, such as pine forests in western North America, have adapted to the ongoing presence of native pine beetles, so that the cycle of insect outbreaks, tree mortality, fire, and regeneration are a characteristic of the ecosystem (Logan and Powell, in press). Climate change, however, has the potential to disrupt these co-adapted relationships, through increases in the size or frequency of outbreaks and through the spread of insects to locations that were previously unsuitable for outbreaks.

Exotic insect species such as gypsy moths can also have substantial impacts on their host trees, with the potential for increasing the spread of exotic insects under climate change. For example, gypsy moths have the potential to cause serious damage to high elevation aspen stands, if climatic conditions become suitable for establishment (Logan et al., in review).

Insect outbreaks occur when a mass attack of individuals are able to overcome the defensive mechanisms of host trees. Because insects are cold-blooded (poikilothermic) organisms, temperature has a significant effect on insect life cycles. For example, some insects typically have a two-year life cycle with high overwinter mortalities that keep its population in check. If temperatures become warmer and insects can complete a life cycle in one year, an outbreak can happen (Logan and Powell, 2001). As a result, increased summer warming caused by climate change could result in areas that were previously less suitable habitats for different types of insect outbreaks becoming vulnerable to massive outbreaks. In addition, drought and heat stress caused by climate change can make forests more vulnerable to attacks (Colorado Division of Forestry, 2004).

Significant changes in the intensity of native or exotic insect outbreaks in western forests, such as the forest around Aspen in the Roaring Fork Valley, could have detrimental effects on ecological processes and sensitive species, as well as the quality of life in the Aspen area and its tourism economy. There may also be interactions between insect outbreaks and wildfire. The objective for this section of the report is to use the existing information to assess the factors that may increase or decrease significant native or exotic insect outbreaks in the Aspen area under different climate change scenarios. Native pine and spruce beetles are discussed first, followed by an examination of exotic gypsy moth risks.

Pine beetles and spruce beetles

For mountain pine beetles, Logan and Powell (2001) consider a temperature cycle to be "adaptive" if the beetle population completes a lifecycle in a single year (univoltine), the emergence of adults takes place at the same time (synchronous emergence), and the emergence occurs at an appropriate time of year. When temperature cycles are not adaptive and spring and summer temperatures fall below a threshold, more than one year is needed to complete the beetle life cycle. This leads to high rates of mortality during the winter and a low likelihood of outbreak. Increasing temperatures allow larval stages to develop more quickly so that the life cycle is completed in one year.

Logan and Powell (in press) have documented cases of novel pine beetle outbreaks that appear to be related to a recent trend of increasing summer temperatures. In the Stanley Basin in Idaho, summer temperatures increased from the mid-1980's to the present. The temperature regimes before 1995 resulted in generations being completed in more than one year (fractional voltinism; four generations in five years), with high winter mortality. Since 1995, temperatures have been sufficiently warm to cross the threshold from a maladaptive to an adaptive climate that supports single-year life cycles with synchronous emergence. As predicted, the beetle population changed in 1995 from a sub-outbreak population into an exponentially growing outbreak population.

High elevation pines provide another example of beetle outbreaks responding to climate warming (Logan and Powell, in press). In high elevation areas, summer temperatures are typically too cold to allow single-year life cycles, so beetle populations remain at low-level, sub-outbreak conditions. At Railroad Ridge in Central Idaho, model simulations of a whitebark pine forest at 10,000 feet (3,000 m) elevation showed that an increase in mean annual temperature of 5.4°F (3°C) would be sufficient to transform the area into an adaptive habitat supporting synchronous, single-year populations of pine beetles. Logan and Powell (in press) observed outbreak population of pine beetles beginning in 2003 at Railroad Ridge. Although whitebark forests have undergone outbreaks in the past and survived (most notably in the 1930's when summer temperatures were more than 4.5°F [2.5°C] above average), massive outbreaks could threaten the long-term viability of these forests as compared to lower-elevation lodgepole pine, which have coevolved with insect outbreaks (Logan and Powell, 2001).

The spectacular mountain pine beetle outbreaks currently occurring near Vail are likely to be less dramatic in the Aspen area, where the forests are dominated by Engelmann spruce and subalpine fir. Smaller lodgepole pine stands do still occur around the Aspen area, and they likely will see further impacts of pine beetle kill in the next several years.

Spruce beetles also have temperature-regulated life cycles. Models show that warmer summer temperatures cause a shift from a life cycle of 2 years to a lifecycle of 1 year (Hansen et al., 2001). Populations with a 1-year life cycle are able to increase exponentially relative to populations maturing in 2 years. This increases the likelihood of large outbreaks and accelerated mortality of spruce trees (Hansen et al., 2001).

Statistical modeling of spruce beetle populations predicts the proportion of one-year life cycle beetles based on the number of cumulative hours above 17°C (62.6°F) during the 40 to 90 days after peak adult emergence. This model suggests that warmer summer temperatures can lead to increased epidemic-level spruce beetle populations with the potential to affect large areas of spruce trees. Anecdotal evidence suggests that warming temperatures in Alaska were responsible for a large spruce beetle outbreak in 1 million hectares of spruce on the Kenai Peninsula (Holsten et al., 1999; as cited in Hansen et al., 2001).

Outside of Aspen, there is an outbreak of spruce beetle in the Baylor Park area. The outbreak developed after a 1999 wind throw event that affected 2,000 to 3,000 acres of spruce, fir, and aspen trees (USDA Forest Service, 2005). The outbreak was the result of spruce beetles naturally moving into the highly susceptible wind thrown lumber and is not necessarily linked to climate change. Tom Veblen at the University of Colorado, stated in 2004 that, "We don't see any evidence that spruce beetle outbreaks [in Colorado] are outside the range of outbreaks over the last few hundred years." Nevertheless, the current outbreak near Aspen indicates the vulnerability of Aspen's spruce forests to ongoing outbreaks of spruce beetles. The spruce beetle infestation in the downed trees put standing trees at an increased risk of a spruce beetle epidemic because the beetles in the wind thrown lumber complete their life cycle and then fly into the standing trees to lay more eggs. Healthy trees may, in some cases, be able to maintain resistance to the beetles, however, in a climate changed scenario, drought-stressed trees are at an increased risk of a small outbreak becoming a full-scale epidemic.

Gypsy moth

European gypsy moths were introduced to North America in Boston in 1869. Gypsy moth caterpillars are considered serious pests because they can defoliate over 500 species of broad-leaved and coniferous trees, leading to tree mortality (USDA, 2005). Oaks and aspens are considered to be preferred host species. Gypsy moths are a serious problem in the northeastern United States, where populations are contiguous and spreading toward the Midwest and South.

Similar to pine and spruce beetles, gypsy moth life cycles are driven by temperature. In particular, a climate is suitable for gypsy moth establishment if there is enough winter cold to complete diapause, summer temperatures are warm enough to complete a one-year life cycle, and egg-laying (oviposition) occurs early enough in the year to complete pre-diapause development before winter (Logan et al., in review). Diapause is a period during which growth or development of an insect is suspended and physiological activity is diminished, sometimes in response to adverse environmental conditions. There is an occurrence of gypsy moths introduction into western states each year because of the high amount of traffic by tourists traveling by vehicle from eastern states. Usually the climate in the West is unsuitable for gypsy moth reproduction; however, changes in climate from unsuitable to suitable conditions can lead to a higher probability of gypsy moth establishment.

A recent analysis by Logan et al. (in review) examined the risk of gypsy moth establishment for several different sites in Utah where adult gypsy moths were detected in traps. At a high elevation site in the Uinta Mountains (approximately 9,000 feet [2,743 m] following a large gathering of visitors, gypsy moths were found. This indicates that the moths may have been brought in by the visitors. Climate simulations indicated that the current likelihood of establishment is very low, but by the last quarter of the 21st century, most aspen in that area would be considered to be at high risk of successful gypsy moth establishment because the climate could become suitable for gypsy moths. In an urban Salt Lake City neighborhood at approximately 5,000 feet (1,524 m) in elevation, the risk of establishment was ranked high (80% to 100% chance), based on current climate conditions and the presence of oak as a native host species. At a Summit County, Utah site at approximately 6,300 feet (1,920 m), the risk of establishment was estimated at a 60 to 80% probability based on current climate, with increasing risk based on projected climate warming. This site is near native aspen stands, which could also be at risk from gypsy moth establishment.

In Colorado, isolated outbreaks of gypsy moths occur as a result of accidental long-distance transport of egg masses by humans. Discovered gypsy moth populations in Colorado have been eradicated with chemical and biological controls. The Cooperative Extension Service of Colorado State University considers gypsy moths to be a risk to broadleaf trees below 10,000 feet (3,048 m) in elevation, with particular areas of concern being "urban shade trees and ornamental shrubs, tree nurseries, low-elevation aspen, 'oak brush' or Gambel oak, vegetation along rivers and streams, and West Slope orchards" (Leatherman et al., 2005). Climate change, however, could broaden the areas at risk, and potentially include high-elevation aspen stands, if temperature regimes became favorable.

> Warmer summer temperatures can lead to increased epidemic-level beetle poputations. In addition, drought and heat stress caused by climate change can make forests more vulnerable to insect attacks.

Potential changes in insect outbreak risk under different climate scenarios

Site-specific modeling of the risk to Aspen forests from insect outbreaks under different climate scenarios has not been undertaken, but could be completed in the future given the climate scenarios developed for this project. Site-specific modeling would pinpoint particular insect outbreak threats and could be used to develop a "rapid response" management plan that would be triggered when climatic conditions surpass certain temperature thresholds and indicate a high risk of outbreak. In the absence of site-specific modeling for Aspen, a general assessment of risk can be made based on the climate scenarios developed for this project.

The summary of climate scenarios developed for this project suggest increases in mean annual temperature of approximately 2 to 4°F (1 to 2°C) for the Aspen area by 2030 and 7 to 11°F (4 to 6°C) by 2100. All of the scenarios predict increases in summer temperatures, with summer temperatures generally increasing more than winter temperatures. These general results suggest that the risk of insect outbreaks may increase based on a greater likelihood of life cycles being completed in a single year. Although the general trend of increasing temperatures suggests an increased risk of insect outbreak, it is important to note that modeling has not been completed to determine how close the Aspen area is to different temperature thresholds for insect life cycles. In addition, the temperature life cycle models can only predict an increased risk of insect outbreaks based on changes in insect population dynamics (i.e., life cycles completed in one year); the models do not guarantee that an outbreak will occur. The risk of insect outbreaks can be influenced by issues including the health of individual trees being attacked, forest stand conditions (density, tree age, species composition), the role of symbiotic organisms (such as fungi) that may coexist with insects, and other factors that affect insect dynamics.

The risk of insect outbreaks could be one of the most dramatic effects of climate change on Aspen's forests.

Changes in precipitation under climate change also can influence the risk of insect outbreaks. The models vary in their estimations about precipitation, with some models estimating increased precipitation and others estimating decreased precipitation. Even if precipitation increases on average, the risk of periodic drought in this area will remain. Forests stressed by drought and increased heat are more vulnerable to insect and pathogen outbreaks. For example, the Colorado Division of Forestry (2004) reported that aspen stands in Colorado "show impacts from drought as evidenced by myriad diseases and insects, including cankers, decay and root diseases, wood borers, and bark and ambrosia beetles in dead and declining trees."

Unlike biome shifts in response to climate change, which are likely to happen slowly because of the long life-span of trees, insect outbreaks can result in a dramatic reshaping of forest qualities in a short period of time. In the Aspen area, climate change, including increased temperature and periodic drought stress, could lead to increased vulnerability of spruce-fir forest to widespread spruce beetle attacks, increased spread of pine beetles to lodgepole pines, and successful gypsy moth attacks on high-elevation aspen stands.

Although these potential impacts are still speculative, the risk of unprecedented insect outbreaks could be one of the most dramatic effects of climate change on Aspen's forests.

4.3 ECOLOGICAL PATTERNS

The vegetation modeling used in Section 4.2 provides a generalized approach, incorporating relationships between climate and plant/animal dynamics, to evaluate how climate change could affect ecosystems. It is also possible to address this topic from the ground up, looking specifically at the Aspen area's local ecological communities and processes, and drawing from theoretical understandings to project potential changes. Neither approach is an exact science, hence drawing information from both helps create a stronger foundation for thinking about Aspen's natural environment within the context of climate change.

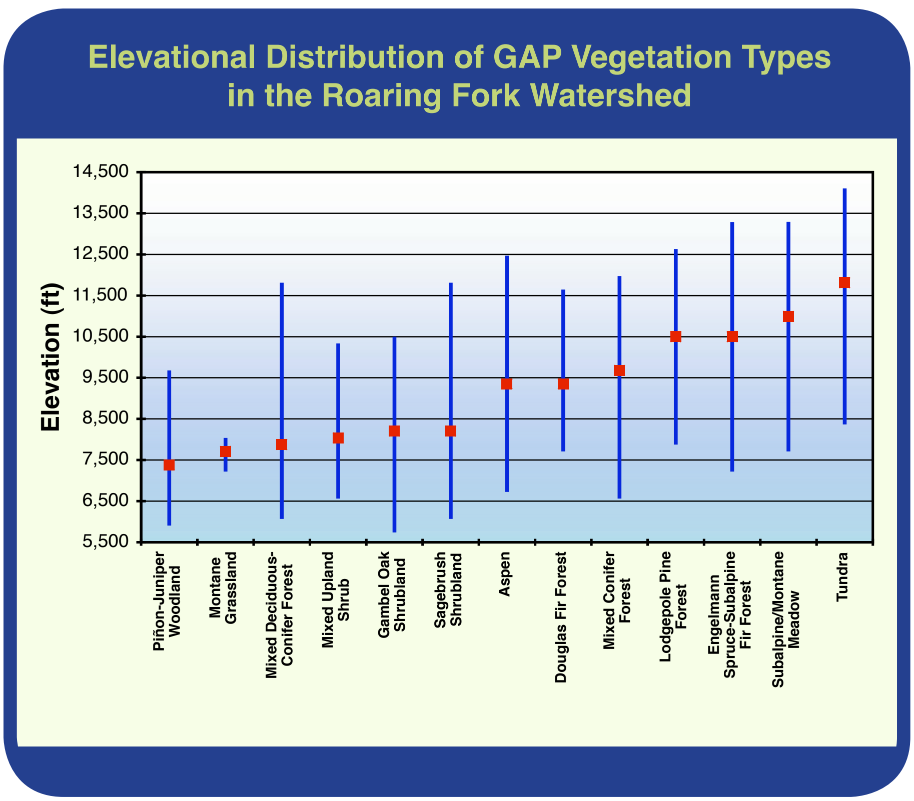


FIGURE 4.6: **Elevational distribution of GAP vegetation types (CDOW, 1998) in the Roaring Fork Watershed.** The red square indicates the median of the vegetation type's elevational range.

This section explores Aspen's ecological communities and processes and how they might shift with changes in precipitation and temperature. It also references the results from studies that have documented shifts in flora and fauna already taking place in mountain environments.

Ecologists are concerned with the effects of climate change on biological diversity, from extinctions of single populations of highly habitat-specific endangered plants to the extirpation of entire species, communities, and ecosystems.

Geographic Distribution of Generalized GAP Primary Vegetation Types in the Roaring Fork Watershed

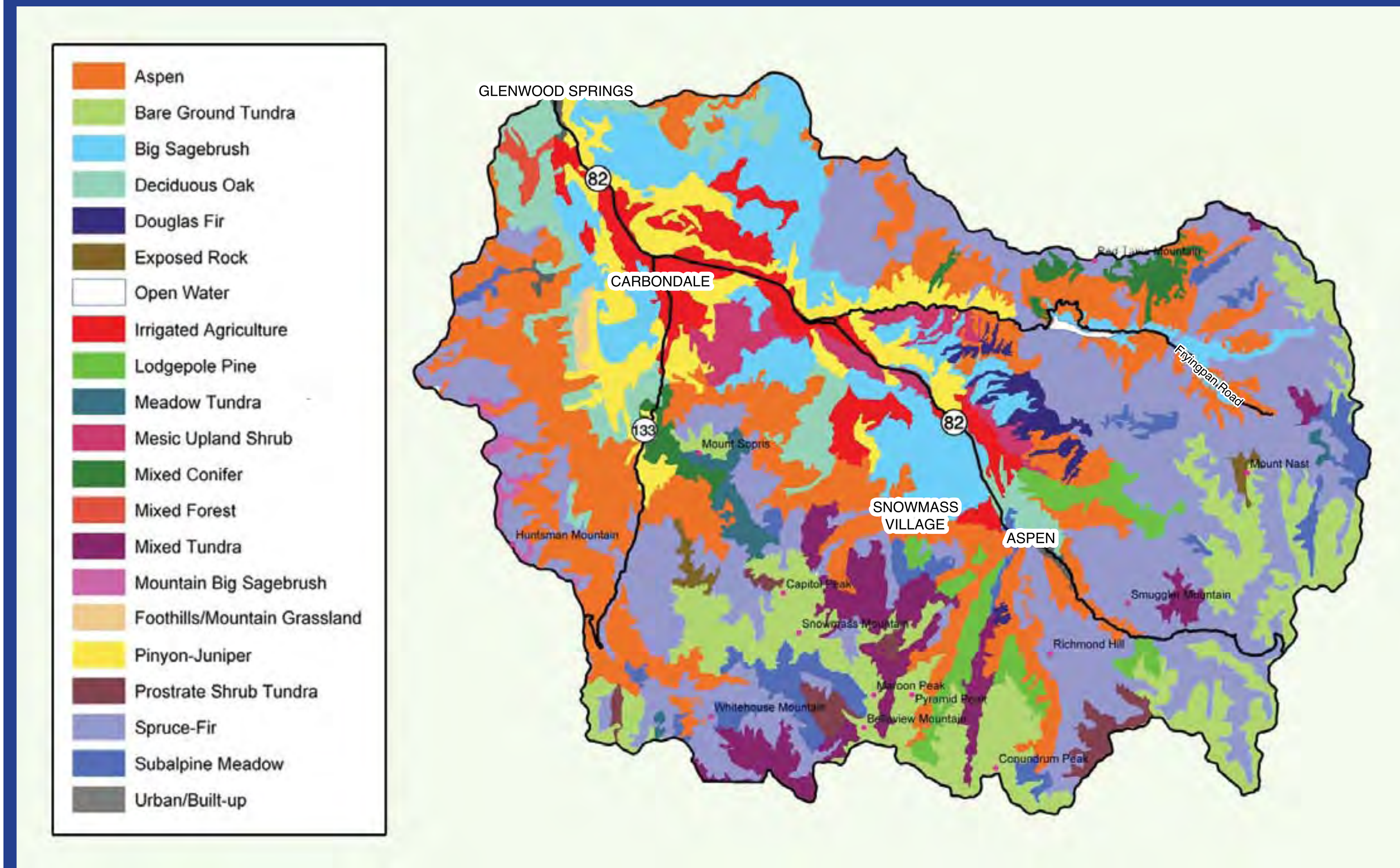


FIGURE 4.7: **Geographic distribution of generalized GAP primary vegetation types (CDOW 1998) in the Roaring Fork Watershed.**

Attempts at reducing the scale of regional climatic forecasts to ecological patterns at local scales must be generalized and accompanied by caveats. Ecologists, however, have long used knowledge of an organism's habitat requirements to predict its presence or absence. Given predictions of large-scale shifts in the distribution of vegetation made by the MC1 dynamic general vegetation model (Bachelet et al., 2001) and the likelihood of increased mean annual temperatures and possible decreased mean annual precipitation, we can attempt to depict future ecological patterns.

4.3.1 Current Ecological Patterns

Vegetation Patterns

The patterns of natural terrestrial vegetation are a reflection of the physical and chemical factors that shape the environment of a given land area. Vegetation patterns in the Roaring Fork Watershed, as in most places, can be largely explained by elevation, aspect, and precipitation (Ricklefs & Miller, 2000; Whittaker, 1975; Whittaker & Niering, 1975). Merriam (1890) used two-dimensional diagrams of elevation and aspect to describe plant community distribution in the Southern Rocky Mountains (Figure 4.6). Since then, ecologists have developed a greater understanding of the intricate interaction between environmental factors (e.g., precipitation, temperature, solar radiation, soils, wind) (Peet, 1981). Several authors have described and/or mapped vegetation patterns in Colorado (Allen et al., 1991; Fitzgerald et al., 1994; Hess & Alexander, 1986; Hoffman & Alexander, 1983; Hoover & Wills, 1984; Kingery, 1998; Peet, 1981; Thompson et al., 1996). The Colorado Gap Analysis Project (COGAP) mapped the extent and distribution of the existing land cover types of Colorado, photo-interpreted from Landsat imagery using a hierarchical classification system (Schrupp et al., 2002; Thompson et al., 1996). Because of the significant topographical variation in the Roaring Fork Valley, the plant associations presented here are simplified using the dominant overstory plant species as a descriptor. Thirteen simplified native plant dominated cover types were mapped by COGAP in the Roaring Fork Valley (CDOW, 1998) (Figure 4.7).

Mean Annual Precipitation Data for the Roaring Fork Watershed

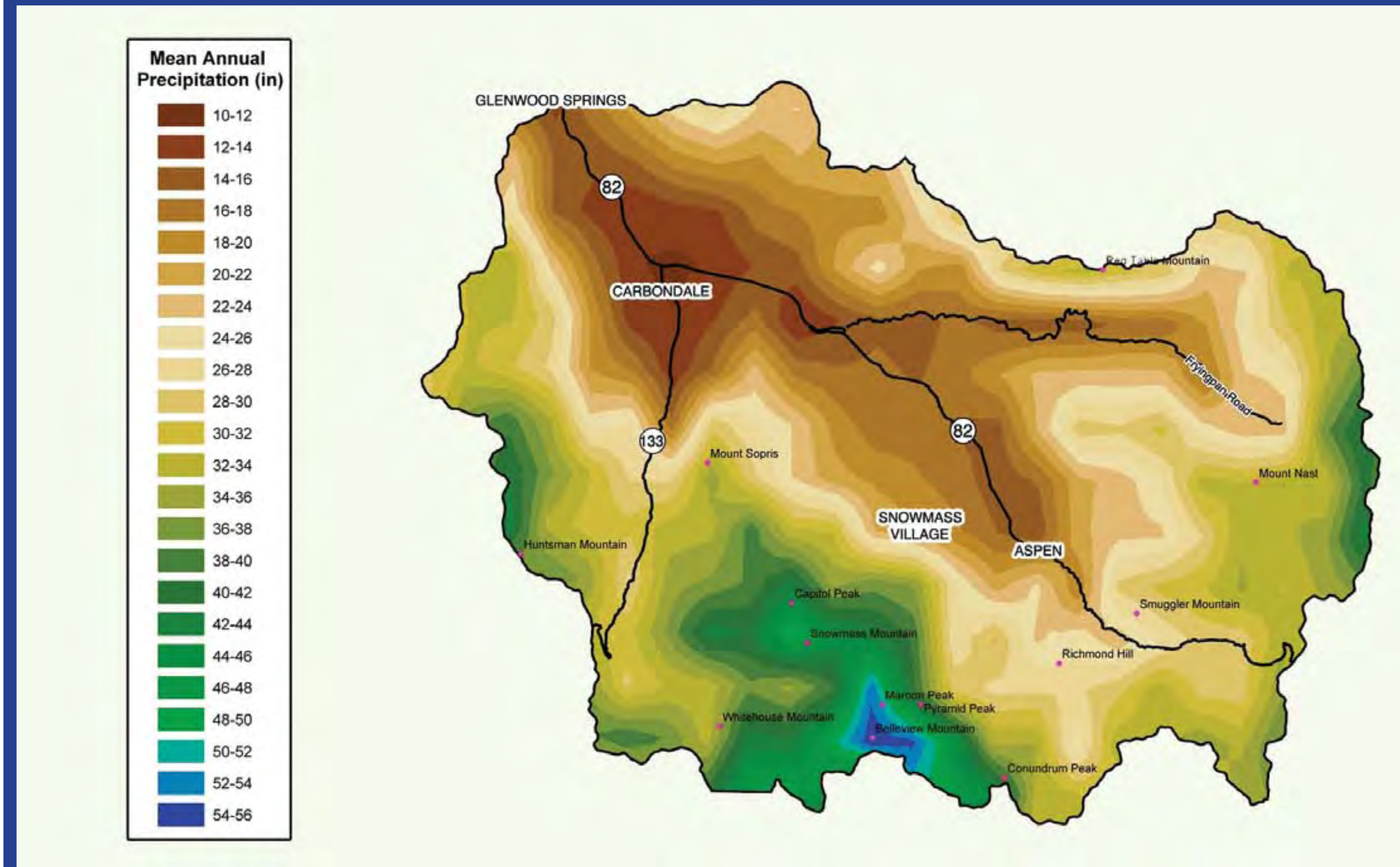


FIGURE 4.8: **Mean annual precipitation data for the Roaring Fork Watershed for the period 1961-1990, produced by the PRISM precipitation model (Taylor and Daly, 1998).**

Strongly influenced by elevation and aspect, the vegetation of the Roaring Fork Valley can be categorized into 7 major life zones: (1) grassland; (2) shrubland; (3) mixed conifer woodland; (4) riparian woodland; (5) mixed-conifer forest; (6) deciduous forest; and (7) alpine tundra. These types can be further broken down based on the major overstory species which tend to prefer a range of temperature and precipitation determined by slope, aspect, and elevation. Under current conditions one can assume the physical characteristics of a given area based upon the dominant native vegetation and, conversely, predict the likely plant community once the slope, aspect, and elevation are known. As such, the thirteen generalized plant cover types[15,16] in the Roaring Fork Watershed are distributed along a three dimensional environmental gradient as follows:

Aspect - The direction a slope faces with respect to the sun is known as aspect. The influence of aspect has an important effect on the spatial distribution characteristics of plants (Kutiel, 1992). South facing slopes receive a greater amount of solar radiation throughout the day and tend to be warmer and drier. Conversely, north-facing slopes receive very little heat from the sun.

Elevation - As one moves upward in elevation temperatures decrease and precipitation increases (Merriam, 1890). Mean annual precipitation in the Roaring Fork Watershed for the climatological period 1961-1990 varied from 11 inches at Glenwood Springs to 55 inches at Belleview Mountain just south of the Maroon Bells (Taylor & Daly, 1998) (Figure 4.8).

Slope - Where slope is very gentle, broad, and all facing in one direction, the gradient between vegetation types tends to be gradual. The steeper the slope, or the more abrupt the change of exposure (e.g., from west to north), the sharper will be the boundary between the two adjacent types (Figure 4.9). Also, steep slopes magnify the effect of aspect and increase the

15. Some cover type names have been altered from the original GAP descriptors to better reflect the plant composition in the Roaring Fork Valley.

16. Due to the scale of the GAP data, riparian and wetland vegetation types are not included in this analysis.

The Varied Topography of the Roaring Fork Valley

FIGURE 4.9: **The varied topography of the Roaring Fork Valley results in abrupt boundaries between vegetation types.** Here Gambel oak shrublands dominate the southerly aspects of a ridge overlooking Snowmass Canyon while dense Douglas fir forest occupies the northerly aspects.

likelihood of erosion.

For example, the range of piñon-juniper woodland is between 5,905 and 9,678 feet (1,800 to 2,950 m) in elevation (CDOW, 1998). At lower elevations around Glenwood Springs, the environmental conditions on flat and northerly aspects are often suitable to the occurrence of piñon-juniper woodlands. As one proceeds to higher elevations, however, the occurrence of piñon-juniper will be restricted to more southerly aspects and steeper slopes where the range of physical conditions favor piñon pine and Utah or Rocky Mountain juniper.

Animal Patterns

Given the distribution of major vegetation types in an area, biologists can use knowledge of an animal's habitat affinity to predict its presence or absence (Scott et al., 1993). Each plant association in the Roaring Fork Valley supports a corresponding suite of vertebrate species. In terms of their ecological role, animals can be classified as generalists or specialists (e.g., Fox & Morrow, 1981; Futuyuma & Moreno, 1988). A generalist is an organism that can survive under a wide variety of conditions, and does not specialize to live under any particular set of circumstances. They eat whatever suitable food is abundant and thrive in a variety of habitats. Also, generalists are better at adapting to landscapes altered by humans. Some wildlife species, such as coyotes, deer mice, and American robins, use a wide range of habitats and therefore can be found just about anywhere within the valley – from piñon-juniper woodlands at 6,000 feet (1,829 m) to alpine tundra at 13,000 feet (3,962 m).

By contrast, a specialist is an organism that has adopted a lifestyle specific to a particular set of conditions (e.g. feeding only on one type of food, breeding or bearing young in a certain plant community or structural stage) and is less able to adapt to anthropogenic changes. Some of the habitat specialists occurring in the Roaring Fork Valley are listed in Table 4.3.

Most rare, endangered, or extinct wildlife are, or have been, habitat specialists. They were unable to adjust to anthropogenic changes to habitat they needed for some aspect of their life history (Benayas et al., 1999). For example, sage grouse[17] once thrived in the abundant sagebrush shrublands in the Roaring Fork Valley. As white settlers came to the area, these flat areas offered the best prospects for potato farms, hay fields, and settlement. Soon most of the valley floor and other places dominated by the sagebrush shrublands such as Missouri Heights were converted for human use. Consequently, sage grouse disappeared from the valley completely.

4.3.2 Future Ecological Patterns

As described above, the distribution of most plant and animal species are determined to a large extent by climatic factors such as temperature and precipitation. Shifts in the magnitude or variability of these factors in a given location will likely impact the organisms living there. Ecological models predict that the global distribution of biomes will shift as a result of the climate changes associated with increased greenhouse gases (Watson et al., 1997). The distribution, abundance, and composition of the populations of plants and animals within those biomes will also change.

Future Vegetation Patterns

Global climate change vegetation models driven by doubled CO_2 scenarios in a global circulation model typically project dramatic alteration to the current geographic patterns of global biomes (Neilson, 1993; Prentice, 1992; Smith et al., 1992). Current vegetation patterns on a given landscape developed over time within a certain range of environmental variability. Within the scientific community, this historic range of variability (HRV) is a concept used to describe a range of past natural conditions. HRV assumes that ecosystems are naturally dynamic and that native species have adapted to disturbance-driven fluctuations over millennia (Morgan et al., 1994). In the shifting mosaic steady-state concept the

17. It is unclear whether the sage-grouse in the Roaring Fork Valley were northern or Gunnison sage grouse.

vegetation present on the landscape changes (e.g., the Roaring Fork Watershed), but if averaged over a sufficiently long time or large area, the proportion of the landscape in each seral stage of each vegetation type is relatively constant (i.e., is in equilibrium) (Bormann & Likens, 1979). Consequently, the greatest potential for change in the Aspen area will occur when temperature and precipitation shift to levels outside the HRV for extended periods (or permanently).

In order to illustrate possible changes to vegetation patterns, assume that temperature will increase and precipitation will decrease over time. It is very likely that temperature will increase through the century under all climate scenarios. It is less certain what will happen to precipitation, but it is likely that Aspen will receive more precipitation in the form of rain and less in the form of snow. These changes will not be instantaneous. Rather, there will be a significant lag between climatic changes and shifts in vegetation. The ability of organisms to disperse depends, in part, on their own characteristics and their interactions with other organisms. A species' ability to disperse depends on its reproductive capability, its dispersal strategies and, for animals, its mobility (Gadgil, 1971).

Examples of Habitat Specialists in the Roaring Fork Watershed

Species	Habitat
American pipit	Tundra
Black-throated gray warbler	Piñon-juniper woodland
Boreal owl	Spruce-fir forest
Brewer's sparrow	Sagebrush shrubland
Canada lynx	Spruce-fir forest
Golden-crowned kinglet	Spruce-fir forest
Horned lark	Montane grassland; Tundra
Juniper titmouse	Piñon-juniper woodland
Long-legged myotis	Piñon-juniper woodland
Meadow vole	Subalpine/Montane meadow
Olive-sided flycatchers	Spruce-fir / Mixed conifer forest
Pika	Tundra
Pinyon jay	Piñon-juniper woodland
Piñon mouse	Piñon-juniper woodland
Purple martin	Aspen forest
Red-naped sapsucker	Aspen forest
Sage sparrow	Sagebrush shrubland
Savannah sparrow	Montane grassland
Virginia's warbler	Gambel oak / Mixed shrubland
White-tailed ptarmigan	Tundra

TABLE 4.3: **Examples of habitat specialists in the Roaring Fork Watershed.** Populations of habitat specialists are particularly vulnerable to climate change induced shifts in vegetation structure, composition, and/or distribution.

Paleo-climatic studies suggest that few forest tree species would be able to disperse as fast as the projected changes in climate (Roberts, 1989). In addition, every species interacts with others in a wide range of relationships. As environmental conditions change, individual plants will begin to decline at the edges of their current positions. Some species will begin to migrate along an elevational gradient or from one aspect to another. This will, of course, not be accomplished by individuals but over time as seeds find suitable conditions in new locations. Some species, such as aspen, can migrate vegetatively as new suckers find conditions more suitable at some edges of a given clone and less suitable at others. The new plant communities that result from these shifts are likely to be different from current plant communities because individual species will very likely migrate at different rates and have different degrees of success in establishing themselves in new places.

The component of climate change on which most attention has been focused and for which there is the greatest agreement between GCMs, is increasing temperature. There is much literature on the influences of temperature on the distribution of species and on ecological processes. As mean temperature increases in the Roaring Fork Watershed, and environmental conditions begin to shift in aspect and elevation, patterns of vegetation will change. Although there are a number of models predicting changes nationwide, continental, and in global vegetation patterns (e.g., Haxeltine & Prentice, 1996; Neilson, 1995), it is challenging to predict the species composition of future plant communities. Some plants that are consistently found together co-occur by chance. That is, their habitat requirements and range of tolerances happen to be similar across enough of a geographical area that humans have categorized them as being part of a plant community, association, alliance, etc. Other plants, however, have symbiotic relationships that necessitate co-occurrence. Consequently, plant community composition could significantly change. As the spatial distribution of environmental conditions shifts, the common range of tolerance of some species will spatially converge while others will separate.

For example, the lowest elevations of the Roaring Fork Watershed, which are the warmest and driest, are dominated by big sagebrush, piñon-juniper woodlands, and Gambel oak shrublands. At higher elevations, these plant communities shift in aspect and elevation. At the confluence of the Colorado River and the Roaring Fork River in Glenwood Springs, the sagebrush shrublands occur largely on relatively flat aspects (the valley floor, benches, and mesa tops) and are dominated by basin big sagebrush[18] or Wyoming big sagebrush with xeric secondary shrubs such as greasewood, fourwing saltbush, and ephedra. Piñon-juniper woodlands, the most extensive vegetation type in Garfield County (Lyon et al., 2001), occur on all aspects and slopes and are dominated by two-needle piñon and Utah juniper. The understory is composed largely of bare, cryptobiotic soils with sparse grasses. Similarly, Gambel oak shrublands at Glenwood Springs occur on all aspects and slopes but tend toward slightly higher elevations than piñon-juniper woodlands. Common secondary shrubs include basin and mountain big sagebrush, alderleaf mountain mahogany, antelope bitterbrush, rabbitbrush, and Utah serviceberry.

In contrast, big sagebrush, piñon-juniper woodlands, and Gambel oak shrublands occur at higher elevations around the city of Aspen as well, but species composition and spatial distribution are different. Big sagebrush shrublands around Aspen are dominated by mountain and subalpine big sagebrush with secondary shrub species such as mountain snowberry and Saskatoon serviceberry. At Aspen, mountain and subalpine big sagebrush shrublands occur on flat and southerly aspects and are mostly found near or on the valley floor. Piñon-juniper woodlands occur on southerly aspects only and Utah juniper is replaced by Rocky Mountain juniper. The piñon-juniper understory at Aspen has a bare soil component as well, but is far more diverse with a greater density of grasses and forbs than at Glenwood Springs. As at Glenwood Springs, Gambel oak shrublands at Aspen occur on all aspects and slopes but are limited to the lower slopes just above the valley floor. Common secondary shrubs are more mesic and include mountain and subalpine big sagebrush, Saskatoon serviceberry with an understory of elk sedge and mountain lover.

As the climate of the Roaring Fork Watershed warms, some of our plant communities will possibly shift up in elevation and north in aspect. Individual species will shift geographically to areas where environmental conditions are more suitable. Species sensitive to temperature may respond to a warmer climate by moving to cooler locations at higher latitudes or elevations. Over time, the plant communities in the Aspen area may begin to resemble those formerly found in the mid-valley, those around the mid-valley will begin to resemble those at Glenwood Springs and more xeric types, now found near Rifle, Silt, and Grand Junction, may thrive in and around Glenwood Springs and Carbondale.

The greatest stresses to the ecosystem might occur at the higher elevations where the soil moisture is the greatest. Alpine meadows may be invaded by subalpine fir, and rare alpine plants may disappear locally as conditions change. Alpine tundra is one of the most biologically diverse communities in Colorado. More than 40% of the approximately 300 plant species that grow in the Southern Rocky Mountain alpine tundra do not occur below tree line (Hobbs et al., 2003). Tree line will likely migrate upward in the future under warming scenarios. It has been predicted that for every degree Fahrenheit of warming, tree line in the Southern Rocky Mountains could rise 350 feet (107 m) in elevation (EPA, 1997). This will shift habitat for alpine species upslope of this advance. Krummholz patches in the forest-tundra ecotone of Rocky Mountain National Park are growing vertically at an average rate of about 1 m per 27 years, and, if this continues, krummholz may become patchy forest on certain sites (Weisberg & Baker, 1995). Over time these patchy forests could become closed dense stands like those at lower elevations reducing understory plant diversity and overtaking the alpine tundra above Aspen. Most alpine plants will retreat upwards and some will be threatened, either by loss of habitat at high altitudes or of suitable microclimates, or through competition, especially from species moving uphill (Holten & Carey, 1992). Hobbs et al. (2003) predict that with a 9 to 11°F (5-6°C) increase in mean temperatures all of the tundra will be eliminated from the Rocky Mountain National Park (RMNP).

It is likely that although many species will be able to migrate to higher elevation in response to climate change, alpine species will be able to only move so high before they simply run out of room.

In addition, warmer temperatures and more xeric conditions could result in a significant decline in montane, subalpine, and alpine wetlands. Fens, such as those at Warren Lakes, slope wetlands, and willow carrs, each representing significant plant diversity, may not persist if summers lengthen and snowpacks decline.

Future Animal Patterns

Global warming could have serious consequences for wildlife, ranging from species migration to species extinction. Most animals are able to respond to climate change faster than plants. Non-migratory animals, however, are likely to respond similarly to plants as a population (Parmesan, 1996). In mountainous areas such as the Roaring Fork Watershed, non-

18. Sagebrush common names are according to Winward (2004).

migratory animal populations would respond to warming by shifting upward as colonizations and extinctions occur at the upper and lower extents of their geographic distribution (Price & Haslett, 1995). An upward shift would thus be reflected in either a net extinction at the lower boundary or a net colonization at the higher boundary. Range shifts in areas with regional warming trends have been reported in butterflies (Parmesan, 1996), birds (Price, 1995; Thomas & Lennon, 1999), and red foxes (Hersteinsson & Macdonald, 1992).

As described above, there are quite a few habitat specialists in the Roaring Fork Watershed. As plant communities shift in both spatial distribution and species composition these specialists could readily adapt. That is, unless environmental conditions exceed the HRV for their habitat and it either disappears from the area completely or changes enough such that it is no longer suitable to that species. The species most in danger of losing all of their habitat in the Roaring Fork Watershed are those whose current geographic distribution is limited to the uppermost elevations in the Roaring Fork Watershed. Alpine animals are unlikely to respond quickly as both environmental conditions and vegetation change. They have a narrow range of ecological tolerances and often have low productivity and long generation times that slow rates of adaptive change (Krementz & Handford, 1984). Increased climatic variability and frequency of extreme weather events associated with climate change may adversely impact white-tailed ptarmigan populations (Martin & Wiebe, 2004). Hobbs et al. (2003) suggest that the timing of hatch of young ptarmigan became significantly earlier from 1975 to 1999 in response to increases in April and May temperatures. They simulated the effects of warming on the ptarmigan population in RMNP and found that if they had occurred in the last 20 years, the predicted climate change trends would have led to declines in ptarmigan abundance to the point of local extinction (Hobbs et al., 2003). Given that, in the Great Basin, Murphy and Weiss (1992) estimated that a warming of 5.4ºF (3ºC) would cause habitats to shift upward by 1,640 ft (500 m) and Hobbs et al. (2003) predict that with a 5.4ºF (3ºC) increase in mean temperatures more than 50% of RMNP's tundra will be lost, it is likely that although many species will be able to migrate to higher elevation in response to climate change, alpine species will only be able to move so high before they simply run out of room.

In a recent study, global warming is a likely cause of the apparent extirpation of 7 of 25 American pika populations in the Great Basin (Beever et al., 2003). The locations used for that study are so remote that there can be no factor other than climate change. Pikas are especially vulnerable to climate change for several reasons. Pikas cannot easily move northward, as their habitat is currently restricted to small, disconnected islands of habitat. Although talus within mountain ranges is often more continuous, this is not always the case; some mountain ranges only have habitable talus at lower elevations or in broadly separated patches. Furthermore, pikas generally do not move large distances, as many individuals may spend their entire lifespan within a 0.62 mi (1km) radius (Beever et al., 2003). In addition, pikas do not inhabit burrows (which could dampen extreme temperatures) and are highly active above ground during the hottest months of the year. Earlier senescence of vegetation may mean increased stress for pikas, and hotter temperatures during high activity periods can create direct thermal stress on the animals. Finally, pikas are densely furred, and thus cannot dissipate heat easily.

Species in mountainous areas that have separate seasonal ranges, occupying higher elevations in summer and lower slopes in winter, may adapt by altering their seasonal migrations. Ungulates (e.g., Rocky Mountain bighorn sheep, mule deer, Rocky Mountain elk) occupying higher elevations of the Roaring Fork Watershed in summer are currently forced to move down to limited, lower winter range by the deep snows and low temperatures at high elevations. If these conditions are moderated by climate warming, the animals would be able to remain for most or all of the year in the more extensive, higher elevations and with increased populations. The result would, in actuality, be contraction of overall range. Models suggest that warmer winters and wetter summers predicted by the Hadley model would allow the RMNP elk population to double in size (Hobbs et al., 2003). Warmer winters and drier summers predicted by the Canadian Climate Centre model would raise the equilibrium population size of elk by about 50%. In other words, elk populations in Colorado could significantly increase yet there would be more high quality habitat to support them.

> If winter conditions are moderated by climate warming, elk populations could significantly increase.

There is also a growing body of evidence suggesting that climate change is affecting animal phenology (i.e., the progression of biological events throughout the year). Dunn and Winkler (1999) analyzed 3,450 nest records from across North America (1959-1991) and found that the mean lay date of tree swallows shifted an average of 9 days earlier and that the main factor correlated with this was change in air temperature. Li and Brown (1999) recorded a 10-day advance in nesting by Mexican jays in the Chiricahua Mountains of Arizona between 1971 and 1997. At the Rocky Mountain Biological Lab at Gothic, Inouye et al. (2000) found earlier robin migration and earlier exit from hibernation by marmots. Marmots are emerging from hibernation on average 23 days earlier than 23 years ago and American robins are arriving 5.4 days earlier from their winter habitat. Animals rely on global cues that signal them to migrate or to go into or out of hibernation. The shortening or lengthening of the day length (also known as photoperiod) is a very strong global cue that affects animals regardless of their altitude or the local weather. On the other hand, other cues to which animals respond are temperature, receding snowpack, rainfall, etc. These can be termed local cues. The disjunction between local and global cues could pose problems as the asynchrony grows. Depending on how food sources and other related species respond to changes, wildlife may become decoupled from the many ecological relationships of which they are a part.

> Many mountain species are particularly sensitive to changes in climate. The greatest concern is that rates of change in temperature may be greater than the ability of species to adapt or migrate.

Invasive Plant Species

Invasive plant species have all of the traits needed to respond to a disturbance in an ecosystem—ability to disperse and the ability to reproduce rapidly. As fire and insects are seen as potentially significant disturbances associated with climate change on the vegetation type and biomass response, invasive plants are the comparable disturbance on the biodiversity of the local ecology (L. Joyce 2006, pers. comm., 30 May). A recent study by Lewis Ziska (2003), suggested that the change in atmospheric carbon dioxide to date may have enhanced the ability of certain invasive weeds to develop. His study includes four species of weeds that are included on the Pitkin County Noxious Weed List (2005): Canada thistle, field bindweed, leafy spurge, and spotted knapweed. Although additional data are needed to link invasive plant survival to climate change, it should not be overlooked that their presence puts additional stress on our native flora and has already contributed to an altered ecosystem in the Aspen area.

4.3.3 Summary of Local Ecological Impacts

Climate change will challenge the ecological systems as well as their component species in the Aspen area and the greater Roaring Fork Watershed. What specific changes will occur is difficult to predict. The literature, however, does provide us with insight into some of the challenges as well as some possible outcomes. First, individuals of a species not only have to be able to disperse successfully, they also have to become established in large enough numbers to reproduce and persist in their new environment. Those that do not disperse or adapt will face local extinction. Second, some extinctions will likely occur prior to adaptations, such as colonization of new habitat. Additionally, many of today's assemblages of organisms (i.e., communities, ecosystems, etc.) are unlikely to exist under future climates. This understanding derives particularly from theories of dynamic biogeography that suggest, as species respond in individualistic ways to changing environmental conditions, that both plant and animal communities change continuously over time (Sprugel, 1991). These theories are based on a large number of paleo-ecological studies of a wide range of species. Third, certain characteristics of species are likely to make them particularly sensitive to changes in climate. These include those which are at the edge of their range; geographically localized; poor dispersers; slow reproducers; highly specialized; or migratory. Many mountain species fall into a number of these categories; and many are relicts, having been isolated by past changes in climate (McNeely, 1990; Street & Semenov, 1990).

Overall, the greatest concern is that rates of change in temperature may be greater than the ability of species to adapt or migrate; although this may be a lesser problem in mountain regions, where species may only have to move a few hundred meters upslope, rather than many miles, as would be the case in flatter areas. Consequently, species may become extinct and, at the least, it is probable that ecotypes and genetic variation will be lost. Some species may become more abundant, however, and speciation may occur in response to new conditions (Smith & Tirpak, 1990).

5. SOCIOECONOMICS AND ADAPTATION

5.1 INTRODUCTION

In addition to the potentially dramatic effects of climate change on temperature, precipitation patterns, and natural biological systems discussed earlier in this report, there is the complex question of how climate change will ripple through Aspen's socio-economic climate. This topic is of particular concern given Aspen's development as a world class ski resort. This chapter explores how Aspen's economy could be impacted in the future, with a focus on the ski industry.

5.2 ASSESSING THE IMPLICATIONS OF SNOWPACK CHANGE

While non-trivial changes in climate could potentially result in profound socio economic impacts, several factors greatly complicate forecasting these impacts. First, scenarios of future climate are generalized. People and institutions respond to climate variables like daily high or low temperatures; daily, seasonal and annual precipitation; or even, in the case of ski area management, the many variables that affect daily snow conditions like wind, temperature and sunshine. But climate change scenarios tend to be broader characterizations of climate, such as changes in monthly averages. To explore climate effects in a socio-economic context, this analysis uses snow covered area (see Chapter 3) to represent snow on the Aspen Mountain ski slopes in different elevation bands, and dates at which certain natural snow depths are attained. Fortunately, since this can be compared to current conditions (defined here as the winter of 2000-2001), then people and institutions with an interest in snow conditions should be able to get a sense of what the projected conditions imply for the future.

> **The socio-economic effects of climate change are the costs of adapting plus the cumulative costs and benefits of the climate effects themselves.**

As is common in climate change impact studies, the projections in this section are for specific milestones in the future (e.g., an average year in 2030 and 2100). Given the large uncertainties over the economy of 2100, we will focus mostly on the 2030 scenario.

How might Aspen respond to the projected snowpack alterations described in Chapter 3? As climate change occurs, human systems will adapt, though the efficacy, costs, and residual negative effects of that adaptation are difficult to predict. Some adaptations may be "automatic," or built in to the human institutions as systems designed to respond to fluctuations in, say, runoff or temperature. Other responses may be more extraordinary, as managers observe changes (such as earlier spring melt) and alter operating rules or physical infrastructure accordingly. These adaptations may even occur in anticipation of future changes, especially as decision-makers make long-term investments.

And while adaptation may reduce impacts, it also typically incurs some costs. In sum, the socio-economic effects of climate change are the costs of adapting plus the cumulative costs and benefits of the climate effects themselves. Decision-makers also find themselves constrained by various factors that limit the range of feasible adjustments. These constraints can be physical/engineering, economic, institutional, legal, and, limitations in imagination and innovation. Also, in any institution or community there may be links between adapting to climate change and working to mitigate the causes of climate change. The City of Aspen and Aspen Skiing Company both have formal programs in place to reduce greenhouse gas emissions. It only makes sense for decision-makers to assess potential adaptations in light of their mitigation goals. Another consideration is how climate change will affect competing resorts. While analyzing this is far beyond the scope of this report, it is worth noting that Aspen's success as a destination resort depends on the desirability of other resorts in the future.

Finally, it is important to keep in mind that Aspen's economy will change regardless of climate change between now, 2030 and 2100. Skiing, as a sport, may grow or decline. Summer tourism may become a larger or smaller part of the economy. The economy of Aspen and the downvalley area will evolve. Most observers expect the regional economy to grow and become increasingly diversified, trends which might offer greater resilience to climate change in some sectors (e.g., tourism) but not in others (e.g., water resources).

Methods

In terms of climate change indicators, the most well-suited one for this analysis is snowpack, which is covered in Chapter 3. It is expressed as snow covered area (SCA) and compared to a current, "normal" year. By focusing on this indicator, the study has adopted the phrase "follow the snow," signifying the connection between snow and the ski industry. The study team performed the following tasks:

- Linked the snowpack scenarios to changes in skiing and ski conditions;
- Assessed how changes in skiing affect the local economy;
- Assessed the potential for adaptation to reduce the effects of altered snow conditions on the skiing economy.

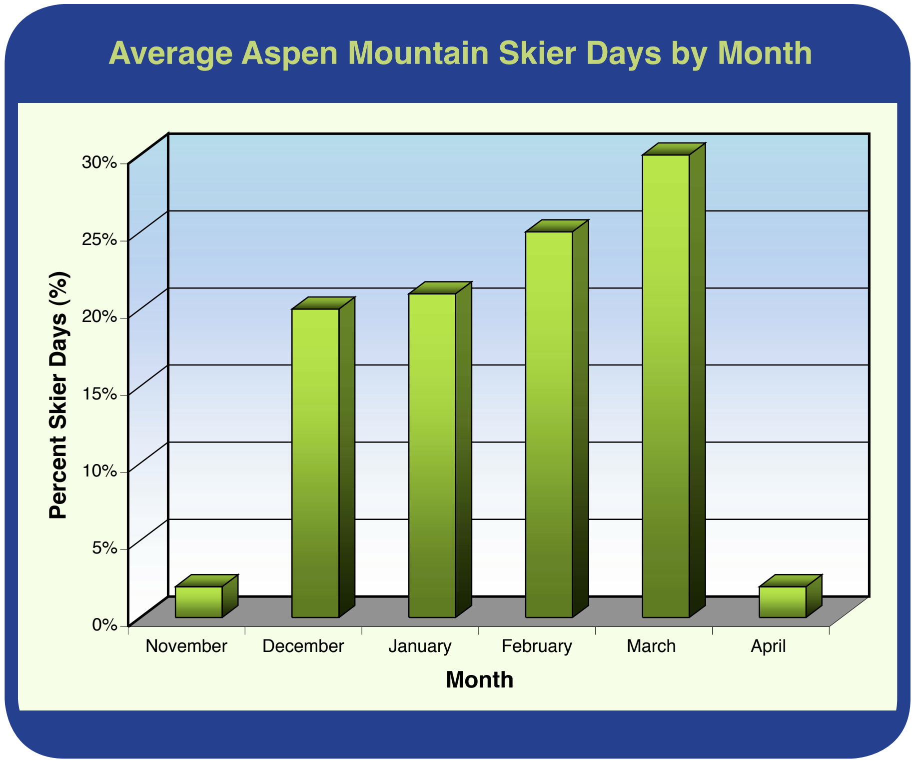


FIGURE 5.1: **Average Aspen Mountain skier days by month, shown as percent of total skier days.** Note: November typically represents one week and April two weeks.

Our approach to the first and third goals relied on interviews of key stakeholders and decision-makers (especially semi-structured interviews with operations personnel at Aspen Skiing Company, ASC). The first phase of these interviews identified operating thresholds and timelines that were used to focus the snowpack modeling on certain dates and factors (e.g., natural snow at high elevations). In the second phase we elicited responses of ski managers to the snowpack projections, both in terms of expected impact and potential adaptations. Also solicited were responses from a broader group of community stakeholders, including city officials, resort business owners, and other citizens in a workshop, and via (forthcoming) reviews of this report.

To link changes in skiing to local economic effects, we developed a relationship between snowpack and skier days, a calculator of the relationship of skier days to direct income and employment, and then applied the skier days scenarios to these relationships. The analysis also involved developing an impact assessment matrix for stakeholders to apply different scenarios and sensitivities, and developed a rough assessment of the role of non-skiing aspects of the Aspen economy.

5.3 RESULTS: IMPACTS AND ADAPTATION

5.3.1 Impacts of Projected Climate Change on Skiing

The study team interviewed Aspen Mountain managers to identify thresholds for operating the mountain, and presented them with the snowpack projections (snow accumulation and melt dates under different scenarios, and dates at which depths of 20 inches (51 cm) and 30 inches (76 cm) at the top of the mountain would likely be attained) to assess how climate change might affect ski area operations. Currently, ASC operates its ski areas roughly from Thanksgiving through Easter. Figure 5.1 shows average skier days by month. In this section, we examine thresholds and impacts related to early, mid- and late season operations.

Early Season Operations and Opening

Aspen Mountain opened for business in January of 1947, and since that time, Thanksgiving has been the target for starting the season. Precise data is not available, but the *Aspen Times* reported that ASC has been able to stay with that target date "6 of every 7 years since opening day" (*Aspen Times*). Notable late starts to the season include 1962 (when there was no snow until Dec 17), 1976, 1980, and 1999. (Table 5.1 summarizes the 1999 experience.) Opening around Thanksgiving has become increasingly important with the development of an early season international ski racing tradition which began with the Roch Cup in the late 1930s, followed by the U.S. Nationals and the North American Championship Series, and most recently the World Cup. Snowmaking, which was initiated on Aspen Mountain in 1982, added more certainty to the opening date and has become an integral part of early season operations, supplementing natural snowfall. Today there is snowmaking capability for all the skiable terrain accessed by all of the lifts except the top of the Ajax Express Lift.

In a "normal" year, mountain managers look for 30 to 40 inches (76 to 102 cm) of snowfall during the first half of November, and a depth of 20 inches (51 cm) on top by November 20, although they can open with as little as 14 to 15 inches (36 to 38 cm) on top. By December 20, managers like to see a 30 inch (76 cm) base on top (which usually requires about 80 inches (203 cm) of snowfall). This allows for 100 percent of the lifts to be open, with nightly grooming.

The snowmaking season generally runs from November 1 to December 15, and hinges on nighttime temperatures. The ideal operating temperature is below 24°F (–4°C). In early November, to maximize economic efficiency snowmakers will wait until that temperature is reached before turning on the machines. By November 15, if snow still needs to be made, managers will turn the machines on at 28 or 32°F (–2 or 0°C). Under ideal circumstances, managers have optimal temperatures to support two weeks of snowmaking (twelve hours at a time) during the first three and a half weeks of November.

As described in Chapter 2, the IPCC Special Report on Emissions Scenario (SRES) A1B scenario, run with the model average, predicts higher temps of 2.5 to 3.5°F (1 to 2°C) by 2030, which means rain in October instead of snow. Snow accumulation start dates will thus be delayed at the top of the mountain by approximately two weeks and at the base by one week. In 2100, snow accumulation at the top will be pushed back by four weeks under the middle emission A1B scenario and by five weeks under the high emission A1FI scenario. It is unlikely that there will be a persistent snowpack at the base in 2100, although under the A1B scenario, there could be snow at the base starting in late November. Also, *most* scenarios predict a decrease in precipitation, which will make snowmaking more difficult and more expensive. The three and a half week window in November for snowmaking will likely be reduced to the two weeks immediately preceding Thanksgiving in 2030 under A1B. It could be a challenge to open the mountain by Thanksgiving, as there will be fewer optimal nights for making snow. Once the mountain has the necessary natural snowfall, most of the snowmaking can be done in 48 hours.

Ski Season Milestones: The 1999-2000 Season

NOVEMBER	
Nov. 20	Targeted opening date
Nov. 25	THANKSGIVING Actual opening date Initially only Little Nell lift open ($10 ticket)
DECEMBER	
Dec. 6	Bell Mountain lift opened ($29 ticket)
Dec. 13	Silver Queen Gondola, Lifts 3, 6, 8 opened ($39 ticket)
Dec. 16	Lift 7 opened ($45 ticket)
Dec. 19	20” base at top (goal is Nov 20)
Dec. 20	Lift 1A and Sundeck Restaurant opened
Dec. 25	CHRISTMAS DAY
Dec. 31	Still only 59% of mtn. open
JANUARY	
Jan 6	30” base at top (goal is Dec 20)
Jan. 21	Still only 29” base
Jan. 22	Snowstorm added 8” new snow, series of storms Jan 22-29
Jan. 29	48” base
FEBRUARY	
Feb. 21	PRESIDENT’S DAY
MARCH	
Mar. 21	76” base (avg max base at top 1995-2002 was 77”)
APRIL	
Closing Day	Finished season with respectable 223” of snowfall on top of mtn. 1999-2000 skier days = 331,121 (average 1995-2005 = 321,472)

TABLE 5.1: **Ski season milestones for Aspen Mountain: The 1999-2000 season.**

In sum, given A1B projections, mountain managers didn’t feel that the Thanksgiving opening date would be affected in 2030. Early season conditions will likely be thinner, but still skiable. By 2100, managers figure that cost considerations might push opening day back to December 15, but they were not too worried about losing the Christmas/New Years week under the A1B scenario. Under the A1FI scenario, however, skiing in Aspen could be a thing of the past by 2100.

It is important to remember that these predictions are averages – there will be better and worse seasons (Wigley, 1988). Table 5.1 summarizes how ASC dealt with delayed snow accumulation in the 1999-2000 season, and how they fared at the end of the season. It provides some insight into how ASC might adapt to similar conditions in the future.

Late Season Operations and Closing

Of secondary concern to mountain managers were the A1B scenario projections of earlier melt dates in the spring. Historically that date has been around March 26 at the base area. According to the projections, the melt date will start around March 21-22 in 2030, and as early as March 2-8 in 2100, when some models show no snow at all at the base by the end of the month. Thus, a decline in quality of conditions will begin earlier, complicating grooming and other aspects of ski area operations.

Normally ASC targets Easter weekend for a closing date, although this date is chosen more out of recognition of skier preferences than climate constraints. In most years there is still plenty of snow in mid- to late April, but people at lower elevations, where temperatures are in the 60's and 70's, are thinking about golf by that time rather than skiing. Given the A1B average 2030 and 2100 scenarios, ski managers were confident that even if there was no snow at the base of the mountain in early April, they would be able to manage skiers by moving snow around and relying on downloading (having skiers ride the gondola down from the top of the mountain at the end of the day rather than skiing down to the base) if necessary. The Aspen Mountain managers did concede that by 2100, they might lose the ability to stay open into April. And again, under the A1FI scenario, the lack of a persistent snowpack in Zones 2 and 3 for most of the year will likely rule out the viability of the ski industry in Aspen.

By 2030, early season conditions will likely be thinner, but still skiable. Under the A1FI (high emissions) scenario, however, skiing in Aspen could be a thing of the past by 2100.

A bigger concern for managers had to do with warmer spring temperatures increasing the likelihood of wet slab avalanches at the ski area. As nighttime temperatures warm, the freeze-thaw cycle is disrupted, causing instability in the snowpack. Currently, wet slab avalanches are only an occasional problem in late March and April, requiring temporary closures on the mountain. Table 5.2 summarizes conditions in spring of 2004, which could become more commonplace as the climate warms.

Ski Season Milestones: The 2003-2004 Season

- **Unseasonably warm March** – especially 3rd week
- **9 days in a row with highs > 40° F** (Mar 19–Mar 27)
- **4 nights in a row > freezing**

  High/Low temps (ºF)
  - **Mar 20: 47/36°**
  - **Mar 21: 50/38°**
  - **Mar 22: 48/33°**
  - **Mar 23: 50/38°**
- Some **terrain closed** due to **wet slab avalanche danger**
  - Control work on Spar Gulch – **temporary closures**
  - **Shadow Mtn lift closed early** due to wet slab avalanches
- 2003-2004 **skier days = 298,831** (avg 1995-2005 = 321,472)

TABLE 5.2: **Ski season milestones for Aspen Mountain: The 2003-2004 season.**

Mid-season Operations
In terms of mid-season impacts, managers speculated that long periods with no new snow could cause grooming challenges. They suggested that new approaches to grooming, and new machinery might be necessary.

Visitor Perceptions and Behavior
Even if ASC is able to muster the necessary technology to open and close as they have historically, many stakeholders told us that visitor perceptions and behavior could be a factor in how climate changes affect the ski economy. Skier visitation and skier days are not only a function of total seasonal snowfall, but also the timing of the first snowfall, snow depth throughout the season, the incidence of warm spells and powder events, media coverage, overall economic conditions, and more general factors like the cache of the town, the après ski scene, culture, shopping, and ease of access. The winter of 1976-1977, and more recently, the winter of 2005-2006 provide good examples of how tightly correlated snowfall is with skier days and a general sense of economic prosperity in the town (see *Aspen Times* articles in Appendix G).

A look at media coverage during the fall of 1976, when there was no snow to speak of until January, suggests a widely held belief among Aspenites that skier visitation is tightly linked to snow conditions as well as the perception of snow conditions. When Senator Floyd Haskell sought to have Aspen declared a disaster area in December of 1976, in need of federal aid, locals were irate, suggesting that such a designation would be devastating for tourism (see Appendix G).

A few related studies focus on the relationship between climate and tourist behavior, and predict how climate change might affect travel and recreation patterns. One visitor survey to Rocky Mountain National Park, for example, found that temperature and precipitation were statistically significant determinants for those who are willing to pay for mountain recreation (Richardson and Loomis, 2005). And in a study of the potential effects of climate change on the Scottish tourist industry, Harrison et al. (1999) speculated that while winter tourism related to skiing may suffer, summer tourism could be enhanced due to a reduction in "dull and damp 'dreich' summer days." Hamilton, et al. (2005) project that the growth rate of international tourism will increase over the coming decades, but may slow down later in the century, as demand for travel saturates. Not surprisingly, they predict that climate change will result in preferred destinations shifting to higher latitudes and altitudes. This will decrease worldwide tourism, since tourists from temperate climates will spend more time in their home countries. Compared to baseline projections of economic and population growth, however, the effects of climate change on international tourism will be small.

5.3.2 Impacts on Skier Days

Even if ASC is able to open and close as they have historically, visitor perceptions and behavior could be a factor in how climate change affects the ski economy.

Information about skier behavior falls under the purview of skiing corporations and their marketing departments and consultants – and was not available for this study. Nonetheless, in an attempt to better understand future climate effects on the Aspen economy, we must establish some linkage between skiing conditions and skier participation.

Skier Days and Climate – a Connection?

Figure 5.2 shows total annual snowfall in town from 1966 to 2005. It can be compared with skier days during that same time period at all four mountains (Figure 5.3) and at Aspen Mountain alone (Figure 5.4). The figures show that the correlation between snowfall and skier days was much tighter before the advent of snowmaking in 1982. Since then, the connection has been dampened, but we maintain they are still related.

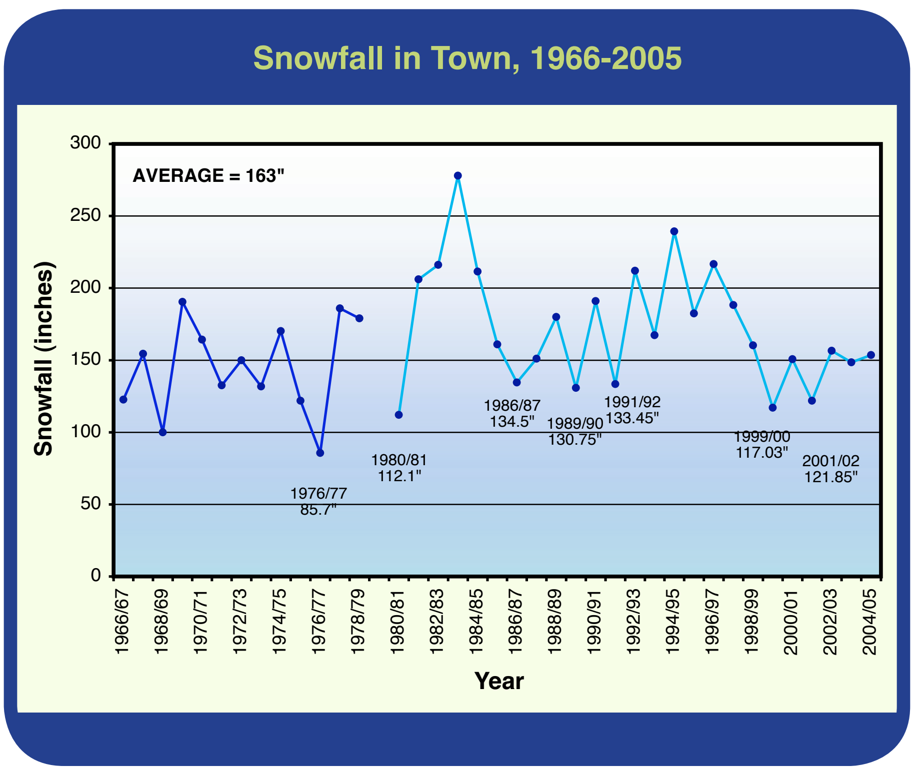


FIGURE 5.2: **Snowfall in town, 1966-2005.** (Data recorded at the Aspen National Weather Service Cooperative Network Station. (Note: The Aspen weather station was moved in 1980 from an in-town elevation of approximately 7945 feet to 8163 feet at the Aspen Water Treatment Plant. Dark blue represents data from the old Aspen station. Light blue represents data from the current Aspen 1 SW station.)

Clearly a wide variety of variables influence skier behavior and this limited analysis does not attempt to systematically account for the many different conditions that might lead to increases or decreases in skier days at any given resort. Examples of conditions and variables affecting market choices not included in this analysis are marketing expenditures at the corporate or state level, international and seasonal events such as X-Games and World Cup Racing, changing age and fitness demographics, travel disruptions, recreation preferences, brand preferences, energy prices – all of which can all have appreciable effects on skier days from one year to the next and at any given resort.

Nonetheless, in search of a climatic variable that may impact future skier days and hence future ski-related economic sectors, we investigated the basic correlation between total seasonal snowfall and the total number of skier days, to better understand how these two variables interact.

Methodology

Data on total season skier days and snowfalls for five Colorado ski resorts were collected: Aspen (all mountains), Vail, Durango Mountain Resort, Telluride, and Wolf Creek Ski Resorts were utilized.[19] These resorts represent a cross section of Colorado resorts, covering destination, Front Range, exclusive, and local markets (Table 5.3). In analyzing the relationship between skier days and snowfall, the previous year was used as a baseline for change.

The influence of non-snow factors on skier days is illustrated in these data by the fact that there are many cases where skier days did not increase (or decrease) when snowfall increased (or decreased). Still, snow and skier days moved in the same direction (a positive correlation) in 37 of the 48 pairs of years in Table 5.3. The magnitude of the correlation can be considered

19. Total skier days at Aspen Mountain, Aspen Highlands, Buttermilk, and Snowmass were utilized although total snowfall at Aspen Mountain was utilized as the representative condition throughout the analysis.

statistically small to moderate (Table 5.4).

In 77 percent of the cases at the five resorts over the ten-year period, the skiers appeared to follow snowfall – as snow increased from the previous year so did skiers, as snowfall decreased – skier days followed suit.

Results

After establishing the level of correlation between total skier days and total snowfall, it was possible to investigate the magnitude of the impact – that is, for an increase or decrease in total snowfall from the previous year, what was the factor of change in skier days? The overall factor was relatively modest, meaning that increased snowfall leads to small increases in total skier days and vice versa, with the few significant outliers likely linked to unique circumstances like economic shock.

The factor of change represents the mathematical relationship between the percentage change in snowfall and the attendant percentage change in skier days. The median factor of change result (reflected in Table 5.5) indicates that for every one percent change in snowfall there is approximately a 0.26 percent change in skier days. Note that the skier day change can move in either a positive or negative direction with the increasing or decreasing snowfall amounts driving skier days up or down. For example, if Vail (or any other ski resort studied) were to experience a ten percent decrease in snowfall next season, it would be reasonable to estimate that it might also see a 2.6 percent (i.e. 0.26 x 10) drop in skier days.[20]

Table 5.5 outlines several statistical indices relating to the factor of change. The radical outliers in the data set were eliminated using the quartile method, however the data set was positively skewed and proved difficult to normalize.

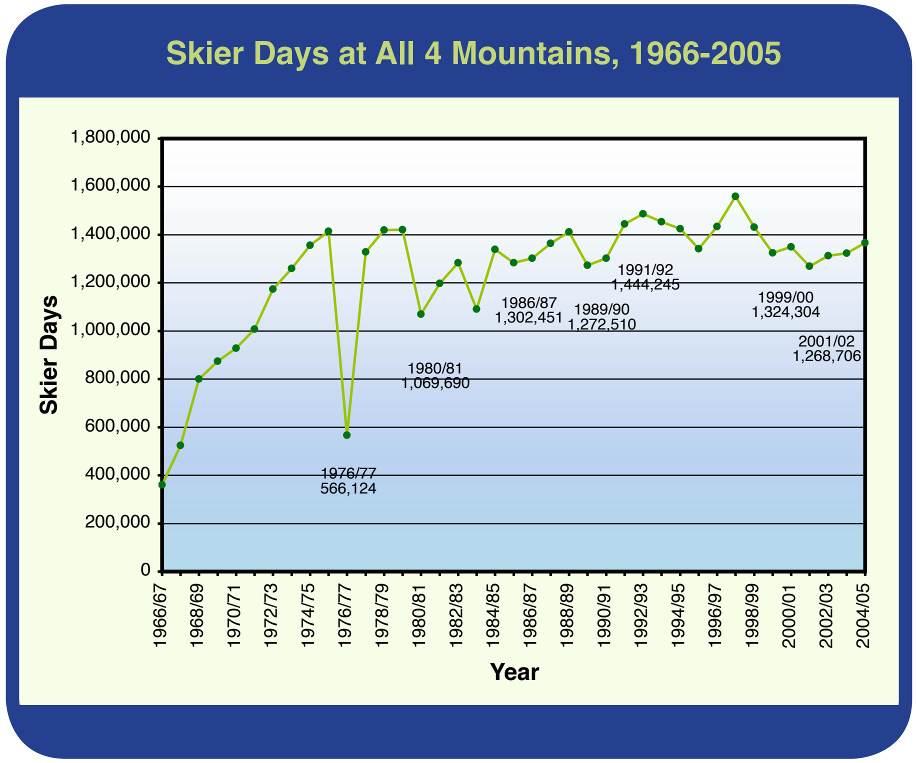


FIGURE 5.3: **Total Skier days at Aspen Mountain, Highlands, Buttermilk and Snowmass, 1966-2005.**

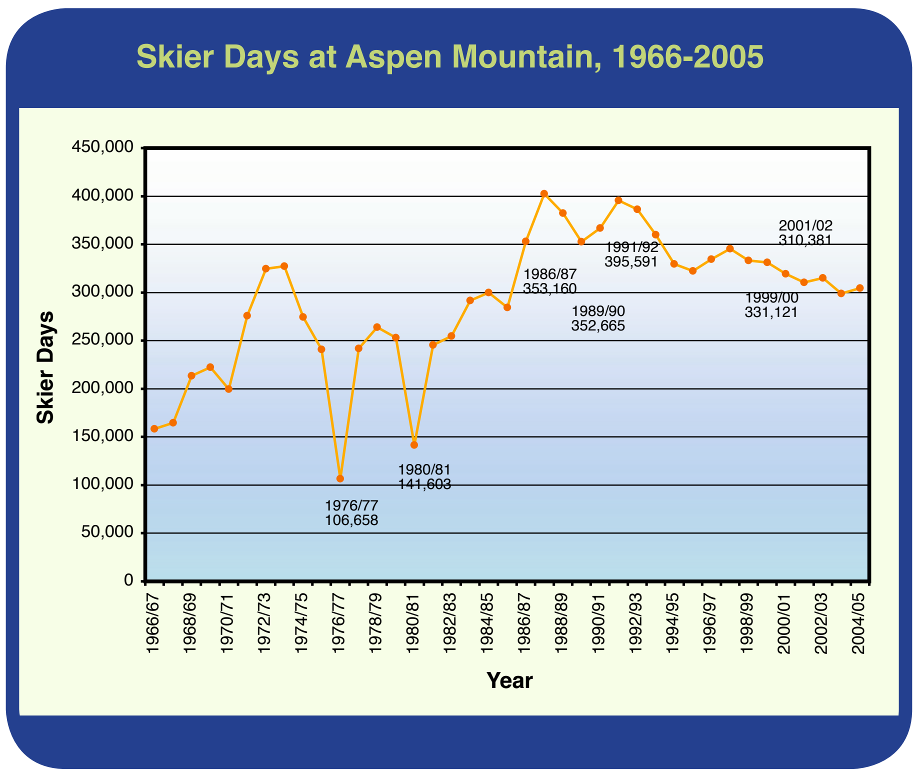


FIGURE 5.4: **Skier Days at Aspen Mountain, 1966-2005.**

20. Again, we acknowledge that a wide variety of variables influence skier behaviors in any given season and are not suggesting that snowfall is the only, or even the most important, variable. This analysis is attempting to establish a relatively simple correlation between total seasonal snowfall and total skier days in an effort to generate a possible spectrum of economic impacts resulting from long-term climate changes.

Total Skier Days and Total Snowfall

	Vail		Telluride		Wolf Creek		Durango Mountain Resort		Aspen	
	Skiers	Snowfall (in)	Skiers	Snowfall (in)	Skiers	Snowfall (in)	Skiers	Snowfall (in)	Skiers	Snowfall (in)
1994-1995	1,568,360	382	301,748	336	157,995		382,839		1,424,771	260
1995-1996	1,652,247	461	270,916	219	124,478	235	307,442	177	1,342,109	240
1996-1997	1,686,790	434	306,507	204	152,971	286	341,643	205	1,434,213	315
1997-1998	1,597,932	339	375,027	232	158,235	233	328,705	182	1,559,386	239
1998-1999	1,334,939	309	382,467	232	202,053	250	304,735	203	1,431,854	189
1999-2000	1,371,702	345	309,737	195	114,802	216	235,000	196	1,324,304	223
2000-2001	1,646,902	370	334,506	185	187,116	292	321,600	193	1,349,050	180
2001-2002	1,536,024	266	341,370	141	170,847	164	250,500	90	1,268,706	162
2002-2003	1,610,961	397	367,252	181	183,907	206	263,712	136	1,313,225	221
2003-2004	1,555,513	189	367,775	221	210,857	273	268,486	193	1,323,633	243
2004-2005	1,568,192	208	411,396	220	215,821	536	278,767	235	1,367,207	185

TABLE 5.3: **Total skier days and total snowfall (in inches) for five Colorado ski resorts, 1994/95 through 2004/05 seasons.**

5.3.3 Economic Impact Analysis – Spectrum of Possible Impacts

It is estimated that skier days in the Aspen area in the year 2030 will be approximately 1.4 million. Using precipitation scenarios for 2030, the next step in the analysis was to estimate impacts on skier days. Skier day and economic projections were *not* extended to 2100 given the impracticality of forecasting economic conditions and skier days almost a century into the future.

The SRES A1B scenario for the average of the five models suggests an annual decrease in precipitation of eight percent by 2030 (see Chapter 2), with a reduction in the portion of annual precipitation falling as snow. Skier day impacts were generated by multiplying the impact factor, derived above, by a percent of change in precipitation increase or decrease. Note that the climate models informing this analysis are variable in their monthly forecasts with regard to precipitation totals and temperatures – that is, the scenarios suggest that some snow months will yield precipitation increases, while other months forecast decreased precipitation and snowfall. To simplify what might turn into a complex monthly analysis of temperature and precipitation that stretches the reliability and usability of climate scenarios, we generated a "spectrum of impacts" that reflects the range of potential increased or decreased winter season snowfall in the year 2030. It was decided to adopt two different potential annual changes in precipitation, ten percent and 20 percent. The resulting spectrum of impacts relates to the total potential decrease or increase in skier days, associated forfeiture or gain of skier-related revenues, and the likely number of jobs in the Aspen and Snowmass Village area that those skier days and revenues support. The spectrum (Table 5.6) offers realistic boundaries on both the positive and negative sides of the ledger.

Correlation Coefficients

Resort	Statistical Correlation Coefficient[21]
Vail	0.37
Telluride	0.23
Wolf Creek	0.50
Durango Mountain	0.38
Aspen	0.39

TABLE 5.4: **Correlation coefficients between snowfall and skier days for five Colorado ski resorts.** Small to moderate correlations illustrate the influence of non-snow factors on skier days.

In addition to considering the climate scenarios we generated three levels of impact analysis for each climate scenario based on the factor of impact (Table 5.5). The low level forecasts change assuming the median, or most conservative, factor change (0.26). The medium level utilizes the average (mean) factor change (0.51), and the high level assumes a dramatic shift of skier days in relation to snowfall changes (representing a nearly one-to-one relationship between snowfall and skier days). What the total skier day

21. Pearson's R correlation Coefficient

and total personal income changes mean in terms of jobs is demonstrated in Table 5.7.

In summary, the steps to calculate the impact factors were as follows:

- Established estimated skier day percentage of change. Each impact assumption factor (low, medium, high) was multiplied by either the 10 percent or 20 percent precipitation increase/decrease scenario.
- Actual estimated skier day change was calculated by multiplying the skier day gain or loss percentage by the 2030 projected skier days.
- Total personal income was derived by multiplying the skier days by estimated skier day revenue (i.e. $226).[22]
- Total jobs were estimated by dividing 2030 skier days by 1000, and then multiplying by three.

Given the available evidence, there is no reason to believe that impacts over the next three decades would be greater or less than the range of potential impacts outlined in Tables 5.6 and 5.7, though we are less willing to speculate on impacts for the year 2100.

Impact Factor Statistics

Median Factor Change (**LOW** Impact Assumption)	0.26
Average (mean) Factor Change (**MEDIUM** Impact Assumption)	0.51
Median + One Std\Dv. (**HIGH** Impact Assumption)	0.91
Standard Deviation	0.65

TABLE 5.5: **Impact factor statistics for a high, medium, and low impact assumption.** The factor of change represents the mathematical relationship between the percentage change in snowfall and the attendant percentage change in skier days.

Climate Change and Job Impacts

Total Change in JOBS +/-			
Climate Precipitation +/-	**LOW** Impact Assumption	**MEDIUM** Impact Assumption	**HIGH** Impact Assumption
10% Scenario	104	207	365
20% Scenario	208	413	730

TABLE 5.7: **Climate change and job impacts.**

Impact Spectrum Summary Matrix

Spectrum of Possible Impacts	2030 Climate Scenarios	Low Impact Assumption			Medium Impact Assumption			High Impact Assumption		
	Precipitation Decrease/ Increase %	**% Chg**	**Estimated Skier Day Change**	**Estimated Total Personal Income**	**% Chg**	**Estimated Skier Day Change**	**Estimated Total Personal Income**	**% Chg**	**Estimated Skier Day Change**	**Estimated Total Personal Income**
Negative Impacts	-20%	5%	-69,300	-$15,937,000	10%	-137,700	-$31,685,000	18%	-243,300	-$55,967,000
	-10%	3%	-34,600	-$7,969,000	5%	-68,900	-$15,842,000	9%	-121,700	-$27,983,000
	0%	**Baseline 2030 Skier Days (1,339,598) & Season Total Snowfall**								
	+10%	3%	+34,600	$7,969,000	5%	+68,900	$15,842,000	9%	+121,700	$27,983,000
Positive Impacts	+20%	5%	+69,300	$15,937,000	10%	+137,800	$31,685,000	18%	+243,300	$55,967,000

TABLE 5.6: **Impact spectrum summary matrix.**

22. See Table 5.13.

5.4 ECONOMIC EFFECTS

What might such changes in skier days mean to the Aspen/Snowmass Village area economy? To assess this we partitioned the local economy into components to isolate those sensitive to climate change, especially changes in ski conditions. While the Aspen area's climate and outdoor setting attracts visitors and residents alike, this analysis focuses mainly on skiing. The process of distilling the economy down to the portion driven by skiing, however, yields qualitative insights into impacts on other powerful economic drivers like second homes, and retiree and amenity migration (amenity migration regards moving to an area permanently or part-time for access to high-quality natural, cultural, and leisure resources).

One of the central efforts in this study is to identify the portions of the economy that are driven by winter visitors, summer visitors, and full-time residents, yielding additional tools for evaluating sensitivity of economic activities to various climatic change scenarios.

5.4.1 Base Analysis

Our analytical approach is best described in a series of questions:

- Economic base analysis: How much of the economy is driven by visitation?
- Isolating the seasons: How much of the visitor economy is driven by winter visitors, summer visitors, and year-round resident spending?
- Contribution of skiing to the winter economy: What portion of the winter economy does skiing constitute?
- Portion of the economic base fueled by skiing: What is the value of a skier day in economic terms?
- The role of skiing in 2030: What is the projected role of skiing in the year 2030?
- Indirect and possible impacts: For second homes, retirees, amenity migrants (an amenity migrant is one who moves to an area permanently or part-time for access to high-quality natural, cultural, and leisure resources) and other residential-based economic drivers, what impacts related to change in visitation and/or in climatic conditions may occur?

Economic base theory operates on the assumption that there is outside demand for a locality or a region's products. When that outside demand grows, the local economy swells, and when demand declines the local economy follows suit. Industries fulfilling the demand are typically referred to as "base industries" or "base drivers." In Aspen, demand for amenities includes: outdoor recreation, lodging, cultural events, eating and drinking, luxury retail, and homes. There is no doubt that tourism is a base industry in Aspen.

Economic base analysis works by categorizing all industry into three classes known as: direct basic, indirect basic, and resident services. There are many variations on this theme, and some economists choose to make the categories more or less complex, but this study's analysis was limited to the following three:

Direct Basic

Direct basic industries are those that bring dollars from outside the local economy. Money must flow into the economy from the outside or else the local economy would soon be bereft of capital, as all of its monetary resources drifted out (from taxes, import of goods, etc.). In western Colorado, money historically entered local markets from the outside when extractive industries, (such as manufacturing or agriculture) sold products to purchasers outside of the local economy. Currently, many of these base industries have been replaced by tourism and its related businesses. This has proven to be a very strong, albeit unpredictable, economic base driver for many communities – especially for destination resort communities such as Aspen.

In Aspen, the direct base industries that fall under the general title of tourism include: visitation, second homes, residents, and regional services. All of these activities are the gateway for outside dollars to enter the local economy. Monitoring the strengths and weaknesses of these industries can tell us much about the economy because virtually everything else is dependant on the base drivers. Growth or decline in the economy can be traced to the health of this sector and scrutiny of the base drivers can allow for some economic forecasting.

Indirect Basic

Indirect basic industries compose the second tier of our three-tiered framework. Indirect basic industries supply the basic industries with the materials and services they need to conduct business. For restaurants, this includes food and liquor vendors, lumberyards for the construction industry, textile manufacturers for the retailers, and linen cleaners for lodging, among others.

Local Resident Services

The final tier of our framework is local resident services. Local residents represent the employees who form the backbone of the labor force supplying the direct and indirect base industries. Employees earn paychecks and in turn, require and

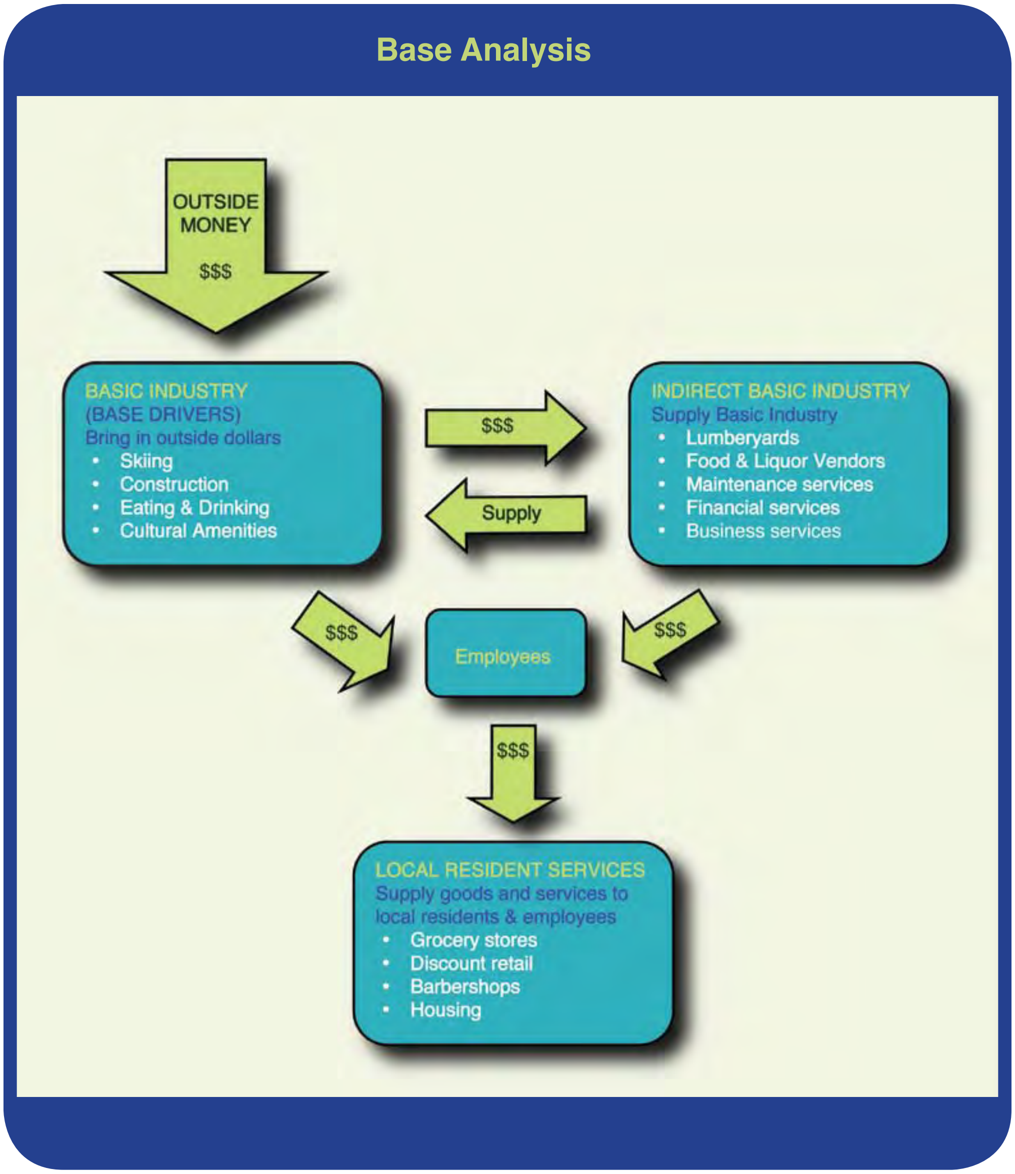


FIGURE 5.5: **Base analysis.**

spend that money for services.

Local resident services are simply the commercial services used in everyday life to maintain a residence. They include but are not limited to: grocery stores, barber shops, hardware stores, discount retail, shoe stores, etc. Clearly, there is some overlap between the categories. For example, some tourists use local grocery stores, and some local residents eat at restaurants built primarily for tourists. Fortunately, there are some reliable and long-standing techniques establishing ratios for how much each industry is utilized by which group of users. Often these techniques are complemented by surveys and "best guesses" by both planners and economists familiar with the region in question.

Another reason to utilize the base analysis framework is that existing data is especially amenable to input and analysis. We are capable of tracking employment and income in each industry type, which allows us to know how strongly each industrial group is performing over time.

5.4.2 Pitkin County Economic Base

The Pitkin County economic base is largely composed of tourism, second homes, households, and regional/national services. Tourism is always a basic activity because visitors bring new dollars into the economy from outside, contributing to the entire economy as described in the previous section.

Second homes act like an economic base in Pitkin County because purchasers and occupants of these homes bring new dollars into the community during construction and development of the home. Additionally, after the home is occupied, both the home and its occupants generate demand for a broad range of goods and services.

Households are an economic driver because of the investment dividends, rents, interest, and transfer payments entering the local economy. Retirees, amenity migrants, and local investors make up the bulk of these households. Transfer payments, or "mail box" income is new money from outside, and so constitutes a portion of the economic base. Regional/national services are an important component of the base because these firms are providing services to customers who are located in different parts of the state or the country. The international architectural and planning firms with home offices in Aspen are an example of regional/national services.

Economic Base: Sensitivity to Change in Visitation
Since potential changes in skier visits resulting from climate change will likely affect the sectors of the economic base differently, it is important to consider: 1) the interface between visitation and economic outputs from each base and, 2) the proportion of activities in each base sector affected by visitation.

Amenity-based economies like that of the Aspen/Snowmass Village area are complex and prone to uncertainties so this analysis focuses on the sectors of the economy where sufficient certainty exists that reduction in visitation will affect each sector's output. To evaluate the interface between visitation and the economic outputs (personal income, sales, etc.) from each base sector, and the proportion of each base sector affected by visitation, the following categories were applied (Table 5.8):

- **Direct Impact:** A change in visitation will affect economic outputs in the sector with a high degree of certainty.
- **Indirect Impact:** A change in visitation will affect economic output of the sector because the industry serves an industry directly affected by visitation (e.g. a linen supply company serving hotels). However, the proportion of the industry serving the visitation sensitive industries is unknown given available data. Unassigned indirect impacts will not be quantitatively evaluated because the linkages between direct and indirect base industries in the resort context presently are not well-understood by economists.
- **No Impact:** The demand for the services or products offered in the sector is unconnected to visitation.
- **Possible Impact:** This category is applied to sectors that are connected to the area amenities as a whole (second homes, retirees, amenity migrants). Given that this impact analysis is evaluating the impact of projected climate change on the economy, it is appropriate to discuss the ways in which these amenity-based markets might be affected by change in one of the amenities (climate conditions-snow fall, etc.) at least in a qualitative fashion.

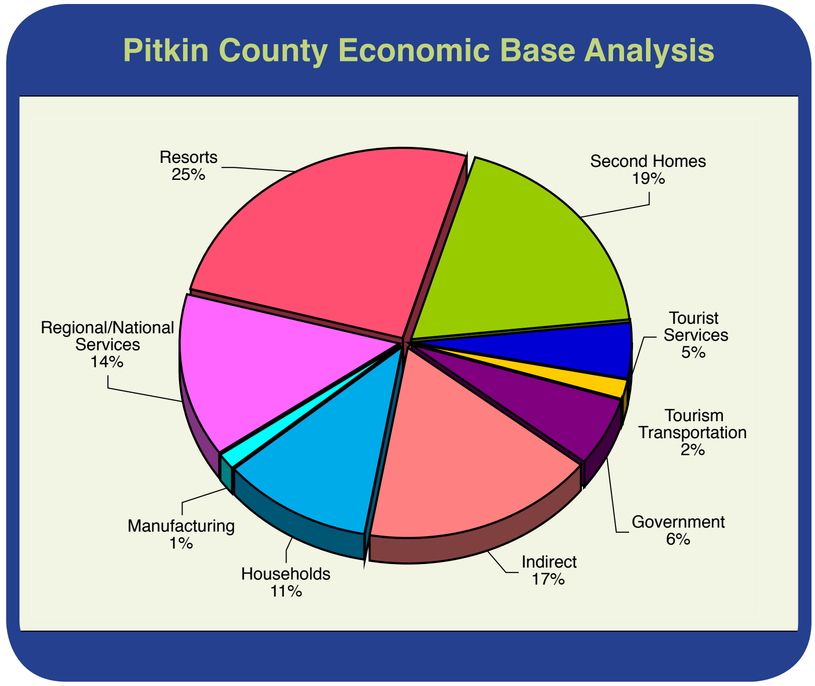


FIGURE 5.6: **Pitkin County economic base analysis.** (Source: State of Colorado Demography Section and the Center for Business and Economic Forecasting)

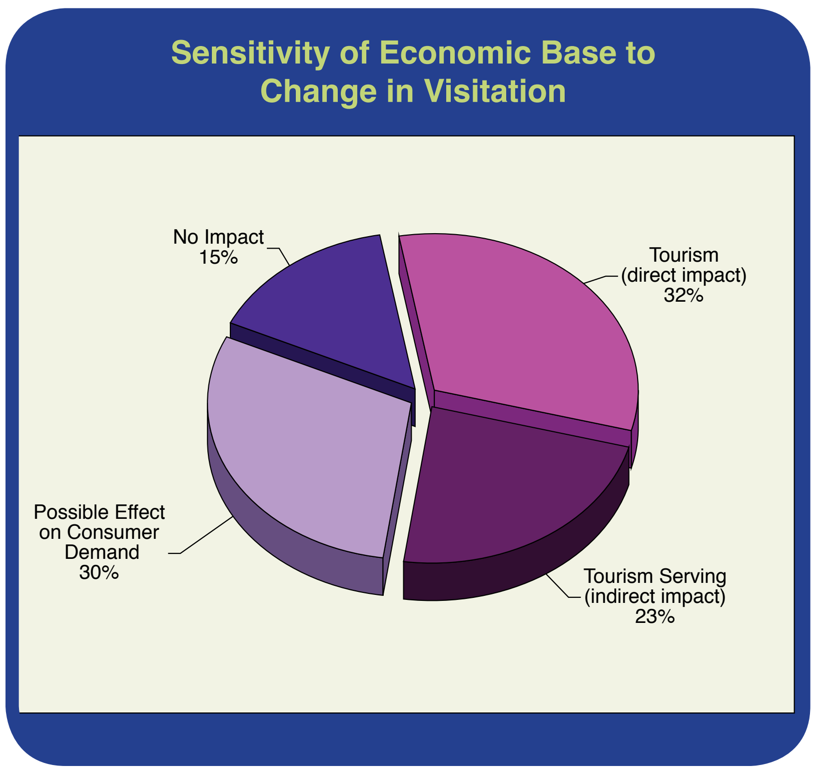


FIGURE 5.7: **Sensitivity of economic base to change in visitation.**

Base Industry Visitation Sensitivity Matrix

Resorts	**Direct Impact:** Resort related businesses would be directly affected by a change in visitation.
Tourist Services	**Direct Impact:** Services specifically targeting the tourist market would be directly affected by a change in visitation.
Tourism Transportation	**Direct Impact:** Services specifically targeting the tourist market would be directly affected by a change in visitation.
Government	**Indirect Impact:** Local governments rely heavily on sales tax in Colorado so fluctuations in visitor spending would indirectly affect government revenues and spending.
Indirect-Unassigned	**Indirect Impact:** To the extent that direct basic industries are affected, orders for supplier and service firms serving them would likely experience some change in activity with changed visitation.
Manufacturing	**No Impact:** Established manufacturing firms should continue to export goods independent of tourism.
Regional/National Services	**No Impact:** Regional/national markets would endure a localized decrease in tourism.
Second Homes	**Potential Impacts:** Skiing is only a part of the total package of amenities offered by the Aspen and Snowmass area. Change of the quality of the skiing amenity and other natural or recreation based amenities could affect consumer decisions.
Households	**Possible Impacts:** Skiing is only part of the total package of amenities offered by the Aspen and Snowmass area. Change of the quality of the skiing amenity and other natural or recreation based amenities could affect consumer decisions.

TABLE 5.8: **Base industry visitation sensitivity matrix.**

Local Resident Spending on Taxable Goods as % of Total Personal Income

Resident Spending on Taxable Goods	% of Total Personal Income
Supermarkets/Grocery	6.00
Convenience Stores	0.10
Beer, Wine, & Liquor Stores	0.80
Health and Personal Care	1.40
Department Stores	1.10
Discount Department Stores	1.60
Warehouse Clubs & Super Centers	3.50
Other General Merchandise Stores	0.40
Clothing & Accessories	2.10
Furniture & Home Furnishings	1.60
Sporting Goods, Hobby, Book, & Music Stores	1.50
Electronics & Appliances	1.30
Miscellaneous Retail	1.50
Eating and Drinking	5.20
Building Material & Garden	3.80
Total Retail Goods	**31.90%**

TABLE 5.9: **Local resident spending on taxable goods as % of total personal income.** (Sources: 2002 Census of Retail; Economic Planning Systems, Denver, CO)

As shown in Figure 5.7, resort activities and tourism, which constitutes about one-third of the regional economic base, would be directly affected by a change in visitation, while 15 percent of the economic base would likely be unaffected by localized change in visitation.

Indirect base industries, amounting to almost one-fourth of the economic base, would likely be affected by visitation, but without intensive firm-by-firm research, we cannot determine this effect.

The consumer demand of future second homes buyers, retirees, and amenity migrants could be affected by a change in quality of a local recreation resource or natural amenity. However, information about this market allows only qualitative assessment of these potential impacts.

Isolating the Seasons
Because skiing occurs only during winter, it is important to isolate the total economic activity resulting from wintertime activities. Seasonality analysis is best accomplished by studying patterns in monthly taxable sales. Seasonal fluctuations in economic activity are readily apparent in the plot of monthly taxable sales during the past four ski seasons. Brief visual examination of Figure 5.8 reveals the importance of winter activity to overall taxable sales, but the actual portion of the sales related to the ski season requires further analysis, which follows in the next section.

FIGURE 5.8: **Monthly taxable sales for Aspen and Snowmass Village, 2000-2004.**

5.4.3 Visitor Spending vs. Local Resident Spending

There are three major components that drive the spending patterns captured in Figure 5.9:

- Winter visitors
- Summer and shoulder season visitors
- Year-round local resident spending

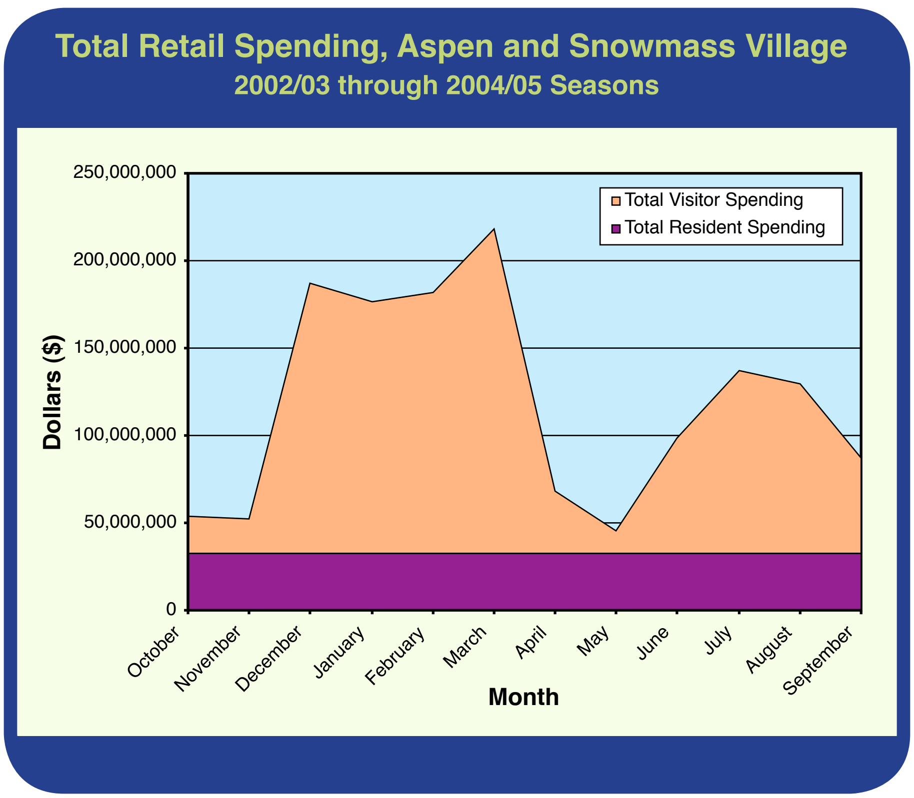


FIGURE 5.9: **Total retail spending in Aspen and Snowmass Village for 2002/03 through 2004/05 seasons.**

One way to isolate visitor spending is to estimate the components of spending that are driven by local resident markets (Table 5.9). According to the Census of Retail and recent work conducted by EPS consulting in Denver, CO, consumers spend about 32 percent of their total personal income on taxable retail goods.

For lower pricing and better selection, many locals do a portion of their shopping in the nearby towns of El Jebel, Glenwood Springs, Rifle, and beyond, so the 32 percent of total personal income spent on retail goods is not all spent in Aspen or Snowmass Village.

Determining the total local resident retail spending occurring in the Aspen/Snowmass Village area is a matter of applying several filters to eliminate out-of-area expenditures. The first filter is to eliminate the portion of the Pitkin County population that is effectively closer to Basalt and/or Carbondale than to Aspen or Snowmass Village. Using 2000 Census block group level data, RPI found that 29 percent of the local resident population lives in the Crystal River Valley, the Frying Pan Valley, or in the Capitol Creek areas, all of which have transportation routes that land these residents in Basalt or Carbondale more easily than in Aspen or Snowmass Village. Therefore, the local resident retail market for the Aspen and Snowmass Village area is 71 percent of the county population, or about 10,500 people.

The Bureau of Economic Analysis REIS database gives Pitkin County's per capita income as $68,504 annually. Table 5.9 establishes that 32 percent of personal income is spent on retail taxable goods. The 2003 Pitkin County Resort Homeowners Survey, conducted by Northwest Colorado Council of Governments, established that on average, Pitkin County households conduct about 57 percent of their spending at their place of residence, meaning that on average, each resident spends a little over $1,000 per month in Aspen and Snowmass Village on taxable goods (Table 5.10). In aggregate, local resident spending accounts for almost $11 million in retail spending in Aspen and Snowmass Village each month.

The difference between the aggregate total annual retail sales for five recent years in Aspen and Snowmass Village and estimated aggregate local resident retail spending for this same time period is the visitor retail spending. Thus we estimate that in recent years, 73 percent of all retail spending in Aspen and Snowmass is from the visitor market, while the remaining 27 percent originates from the local resident market.

Visitor and Local Spending

POPULATION OF LOCAL RETAIL MARKET AREA	
% Population in Aspen/Snowmass Area	71%
Estimated Population Pitkin County 2003	14,874
Estimated Population in Aspen/Snowmass Area	**10,500**
LOCAL RESIDENT MONTHLY RETAIL EXPENDITURES IN ASPEN	
Per Capita Personal Income 2003	$68,500
% Total Personal Income Spent on Retail	31.9%
% Local Resident Spending in Local Retail Market	57%
Per Local Resident Annual Retail Expenditures in Aspen & Snowmass	$12,500
Per Local Resident Monthly Retail Expenditures in Aspen & Snowmass	$1,040
Aggregate Monthly Retail Spending in Aspen and Snowmass by Local Residents	**$10,899,000**
Aggregate Retail Sales in Aspen and Snowmass 2000-2004	$490,154,000
Estimated Aggregate Local Resident Retail Spending 2000-2004	$130,788,000
Estimated Aggregate Visitor Retail Spending 2000-2004	$359,366,000
% Sales from Local Resident Spending	**27%**
% Sales from Visitor Spending	**73%**

TABLE 5.10: **Visitor and local spending.** Figures are rounded. (Sources: US Census Bureau, State of Colorado Demography Section, 2002 Census of Retail, NWCCOG 2003 Resort Homeowner Survey, Pitkin County Results; Aspen Finance Department Retail History Report, Snowmass Village Retail History Report, Bureau of Economic Analysis 2003 Personal Income)

Seasonal Spending

The winter season is November through April, when ski areas are open. Shoulder seasons were combined with summer, since similar motivations for visitation and activities occur in these seasons. Local residents spend steadily each year. The spending peaks are evident when several years of monthly sales are combined (Figure 5.9).

Defining the winter season and identifying the local resident spending isolates the winter visitor spending and summer/shoulder season spending. Resident spending and summer visitor spending account for about one-half of the total spending, with the remaining half accounted for by winter visitors (Figure 5.10).

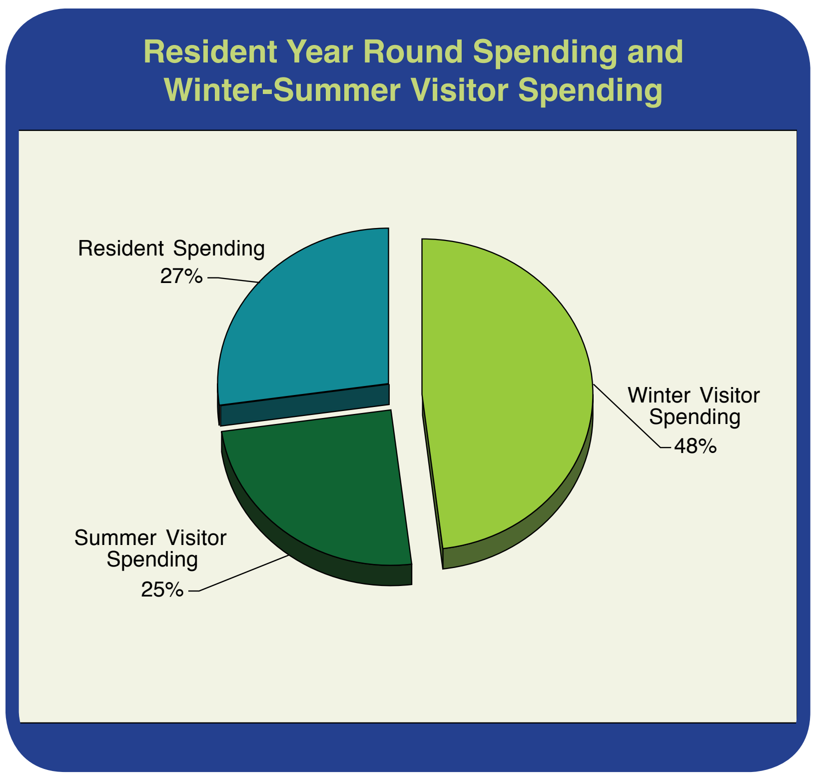


FIGURE 5.10: **Resident year round spending and winter-summer visitor spending.**

Not all sales are taxable, but the reliability and monthly reporting of taxable sales make them the best and only accurate source for measuring seasonal spending fluctuation and contributions. In this analysis, it is assumed that seasonal patterns in retail (taxable) spending reflect patterns in overall spending, including services that are not taxed. This assumption reflects the observation that nearly all businesses in the Aspen/Snowmass Village area, regardless of whether their sales are taxable, are busier during the winter and/or summer than during the shoulder seasons. Confidential ES202 employment and income data by firm, including all employees from all industries, shows a clear pattern of higher average employment during the first and third quarters (winter, summer) than in the second or fourth quarters (spring, fall), further supporting this assumption.[23]

Skier Expenditure Analysis

OVERNIGHT VISITS	
Per Overnight Skier Day Expenditures	$252
Total Taxable Expenditures (on and off Mountain)	$179
Estimated Overnight Skiers 2004-05, 4 Mountains	1,046,248
Estimated Overnight Skier Taxable Expenditures 2004-05	$187,663,000
LOCAL DAY VISITS	
Per Skier Day Spending	$50
Per Skier Day Taxable Spending	$23
Estimated Day Visitor Skiers 2004-05, all 4 Mountains	229,446
Estimated Day Skier Taxable Expenditures 2004-05	$11,472,000
NON-LOCAL DAY VISITS	
Per Skier Day Spending	$50
Per Skier Day Taxable Spending	$27
Estimated Day Visitor Skiers 2004-05, all 4 Mountains	48,670
Estimated Day Skier Taxable Expenditures 2004-05	$2,434,000
Total Ski Visitors Taxable Expenditures 2004-05	**$190,097,000**
Total Winter Visitor Taxable Sales Pitkin County 2004-05	**$244,990,000**
% Skiing as % of Total Winter Visitor Taxable Sales	**78%**

TABLE 5.11: **Skier expenditure analysis.** Estimated expenditures and totals are are rounded to the nearest thousandth. (Sources: Skier and Snowboarder On Mountain Survey 2002-2003, RRC Associates, Boulder, CO, Ski Utah, Salt Lake City, UT; Forest Service 2003 National Visitor Use Monitoring Survey; 2004/05 Demographic Skier/Snowboarder Research, Aspen Skiing Company 4 Mountains Combined, National Ski Areas Association, RRC Associates, Lakewood and Co)

5.4.4 Contribution of Skiing to the Winter Economy

Not all winter visitors ski and some winter visitation is motivated by entirely different attractions and events. The final step in distilling economic activities down to skiing-related activities is to estimate the quantity of winter visitor economic inputs that are related to skiing.

Skier Days and Skier Spending

Publicly available skier expenditure data and the *Forest Service 2003 National Visitor Use Monitoring Survey* reveal the estimated per skier day taxable expenditures for overnight and day visitors. Total expenditures need to be converted to taxable expenditures for a comparison to overall taxable expenditures. The *2004-2005 Demographic Skier/Snowboarder Research, Aspen Skiing Company Four Mountains Combined* provided by Aspen Skiing Company contains survey results upon which to base estimates of the proportions of local and non-local day skiers and overnight skiers for the year. These estimates allow distribution of the total skier days for all four mountains into each category where the respective per skier day expenditures were applied to yield the total estimated skier spending in each category Table 5.11.

Percent of Pitkin County Economic Base Driven by Skiing

% of Total Visitor Sales from Winter Visitors	66
% Economic Base Driven by Visitors	32
% Economic Base Driven by Winter Visitation	21
% of Winter Tourism Economy Driven By Skiing	78
% of Economic Base Directly Driven by Skiing	**16**

TABLE 5.12: **Percent of Pitkin County economic base driven by skiing.**

23. 2002-2004 by firm quarterly ES202 data, Colorado Department of Labor and Employment.

In sum, skiing accounts for 78 percent of winter visitor taxable sales, and this same proportion is assumed to hold for all spending, taxable and non-taxable.

Portion of the Economic Base Associated with Skiing

Given that two-thirds of the total taxable sales to visitors comes from wintertime sales (Figure 5.8), and that 32 percent of the economic base is directly connected to visitation, it follows that 21 percent of the total economic base is driven by winter visitation. Further, because 78 percent of the economic activity in the wintertime is fueled by skiers, it follows that 16 percent of the Aspen/Snowmass Village area economic base depends on skier spending (Table 5.12).

Economic Value (TPI) per Skier Day

	2003	2030
Total Basic Personal Income	$773,568,845	$6,447,602,000
TPI/Basic Income Ratio	1.17	1.17
Skiing Related Basic Personal Income	$112,078,560	$270,938,000
Skiing Related Total Personal Income	$131,131,915	$316,997,000
4 Mountain Skier Days	1,323,633	1,367,000*
Total Personal Income per skier day	**$99**	**$226**

TABLE 5.13: **Economic value (TPI) per skier day.** Estimate uses the percentages described in the section of the report entitled Portion of Economic Base Associated with Skiing applied to the total basic income quantities making up the tourism, or visitor-based sectors of the economic base. Figures for 2030 are rounded to the nearest thousandth. *4 mountain skier days from the 2004/05 ski season were held flat to 2030. (Sources: Colorado Demography Section personal income base industry analysis http://dola.colorado.gov/demog/leifa2.cfm and Center for Business and Economic Forecasting personal income forecasts)

Current and Projected % Economic Base Driven by Skiing

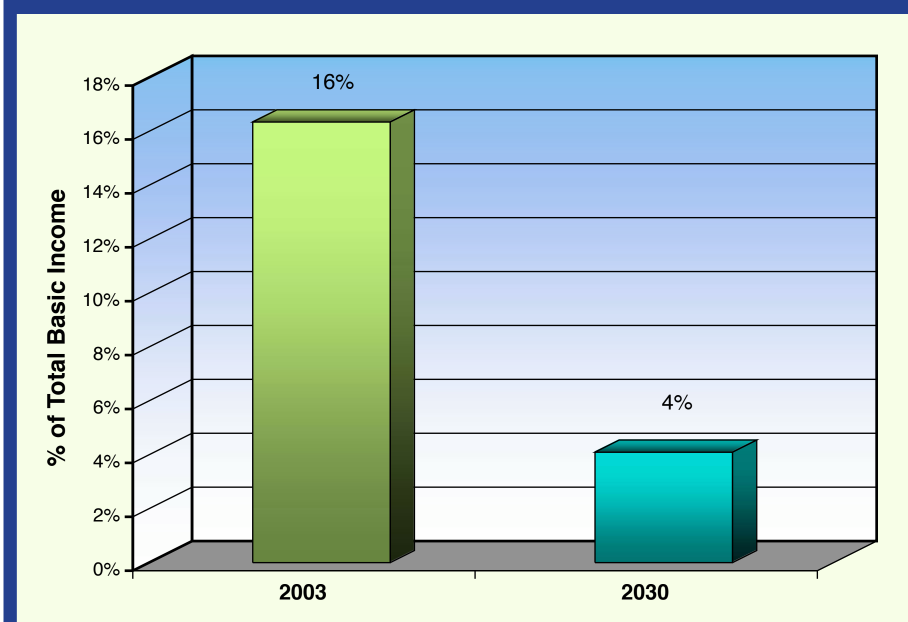


FIGURE 5.11: **Current and projected % economic base driven by skiing.**

5.4.5 Projected Role of Skiing in 2030

Projecting the impact of changes in skier days on the economy now and in the future requires an appropriate metric. The Center for Business and Economic Forecasting in Colorado Springs conducts county-scale economic forecasts available in terms of personal income.[24] These are the best local economic forecasts available, so we chose personal income as the primary metric to represent the economic role of skiing.

The analysis begins by estimating the economic value of each skier day in terms of personal income (Table 5.13). For the purposes of this analysis we prescribe skier days in 2030 as 1.4 million based on past 4 mountain data. Adjusting the 2003 personal income for inflation through 2030 yields a total personal income of $226 per skier day (Table 5.13).[25]

Given the previous section's conclusion that 16 percent of the economic base (basic income) is driven by skiing, the question remains: what portion of the economic base will skiing constitute in 2030? Estimating this entailed dividing the projected total personal income from skiing in 2030 by 1.17, the ratio of total personal income to total basic income presented in the Demography Section base analysis. A parallel analysis was conducted in terms of skiing-related jobs (Table 5.14). While skiing constituted almost one-sixth of the total economic base in 2003, due to the projected decline in skier days and projected economic growth through 2030, skiing will continue to diminish in its share of the economic base (Figure 5.11) to an estimated four percent of the total economic base.

24. http://www.cbef-colorado.com/

25. Applied a historical projection inflation factor of 2.4, the same factor applied to the US Dollar for the years 1978-2003

5.5 VULNERABILITY OF ASPEN SKIING COMPANY TO CLIMATE CHANGE

While this study focuses on how climate change might affect Aspen Mountain operations, a consideration of the ASC's vulnerability must include thoughts on its operation as a whole. This section explores specific vulnerabilities related to Aspen Mountain, and more general vulnerabilities affecting ASC.

Skiing Jobs by 2030 and as Percent of Basic Jobs

	2003	2030
Total Jobs	19,701	43,000
Total Basic Jobs	15,339	33,600
Total Jobs/Basic Jobs Ratio	1.28	1.28
Skiing Related Basic Jobs	3,217	3,200
Skiing Related Total Jobs	4,118	4,100
4 Mountain Skier Days	1,367,207*	1,367,000
Total Jobs per 1000 skier days	**3.0**	**3.0**
Skiing as % of Basic Jobs	**21%**	**9.4%**

TABLE 5.14: **Skiing jobs by 2030 and as percent of basic jobs.** Projections for 2030 are rounded. *2004/05 ski season skier days. See Table 5.13.

5.5.1 Aspen Mountain Vulnerabilities

The biggest challenge facing Aspen Mountain managers as the climate warms will be securing enough coverage on top of the mountain to open on the targeted date. Currently there is snowmaking on 200 of the mountain's 675 acres (2.7 km^2), servicing all of the lifts except the top of Ajax Express. Without snowmaking capacity on top, mountain managers will find it increasingly difficult to secure the minimum snow-depth necessary to open.

A second major vulnerability has to do with the likely increase in frequency of wet slab avalanches in the spring as nighttime temperatures warm. While all ski areas will likely have to deal with this problem, Aspen Mountain is particularly at risk because the slope most prone to these types of avalanches is directly above Spar Gulch (near Kleenex Corner), a main thoroughfare and one of the few ways off of the mountain. Controlling avalanches in this area involves closing off this part of the mountain, seriously limiting top-to-bottom skiing on the mountain during the control work.

> The biggest challenge facing Aspen Mountain managers as the climate warms will be securing enough coverage at the top of the mountain to open on the targeted date.

5.5.2 ASC Vulnerabilities

Without significant adjustment, ASC may lose a week of skiing on both ends of the currently configured ski season (Thanksgiving to Easter). Depending on how flexible the World Cup and other professional ski racing schedules are, this could mean losing the early season racing that has brought so much publicity to Aspen.

While operations managers believe that snowmaking can make up for much of the climate-induced snow deficit, an obvious vulnerability has to do with the additional water, storage, and power that will be necessary to expand snowmaking capacity. Costs and constraints related to using snowmaking as a primary adaptation are discussed below.

Another vulnerability likely to affect all ski areas is that beginner runs tend to be at a lower elevation, where the effects of climate change will be more pronounced. Poor conditions are likely to discourage beginning skiers.

Finally, warm and dry falls could affect visitor perceptions and vacation planning and lead to a decrease in skier visitation, as discussed above.

5.5.3 Elements of Resiliency

ASC's best hedge against climate variability has been and will continue to be its ability to make snow to compensate for lack of natural snowfall. Snowmaking, introduced at Aspen Mountain in 1982, has reduced ASC's vulnerability to climate variability and will continue to do so.

Another key element in ASC's resiliency is the flexibility that comes with having four separate mountains on which to coordinate operations decisions like opening and closing days, race locations, etc. For example, prior to the introduction of snowmaking on Aspen Mountain, ASC was able to avoid canceling early season racing during the fall of 1976 by moving the races to Aspen Highlands, where it had limited but serviceable snowmaking.

Compared to other ski areas in the United States, and elsewhere in the world, ASC is in a relatively strong position due to its location and elevation. Most ski areas in Europe, Australia and even Canada are already experiencing significant effects related to climate change, with corresponding reductions in skier visitation (Elsasser and Burki, 2002; Harrison et al., 1999, 2001; Scott et al., 2003; Whetton et al., 1996). In the United States, ski areas in the Northeast are at a lower elevation and are thus more vulnerable, while ski areas in the Sierra and the Pacific Northwest may be more vulnerable to climate change because of their maritime climate (Hayhoe et al., 2004). Ski areas in the Central Rockies are probably the most resilient to climate change simply because, in this continental climate, winter storms are accompanied by very cold temperatures, well below the threshold for snow instead of rain. Compared to Summit County ski areas, Aspen is more vulnerable because of its lower elevation, though Steamboat is even lower. However, its more northerly latitude gives it an edge on ski areas in the Southwest like Durango Mountain and Taos.

> A key element to ASC's resiliency is the flexibility that comes with having four separate mountains.

Aspen Mountain has a few additional factors that enhance its resiliency to climate change. The gondola is a key tool for adaptation to climate change because it allows for downloading when conditions at the base are not skiable. And Aspen Mountain's meadowy terrain, in contrast to the rocky nature of Snowmass, for example, means that it needs less snow for adequate coverage.

Finally, ASC's significant financial resources give it an edge over smaller operations that are less able to take advantage of evolving technologies for efficient snowmaking and less able

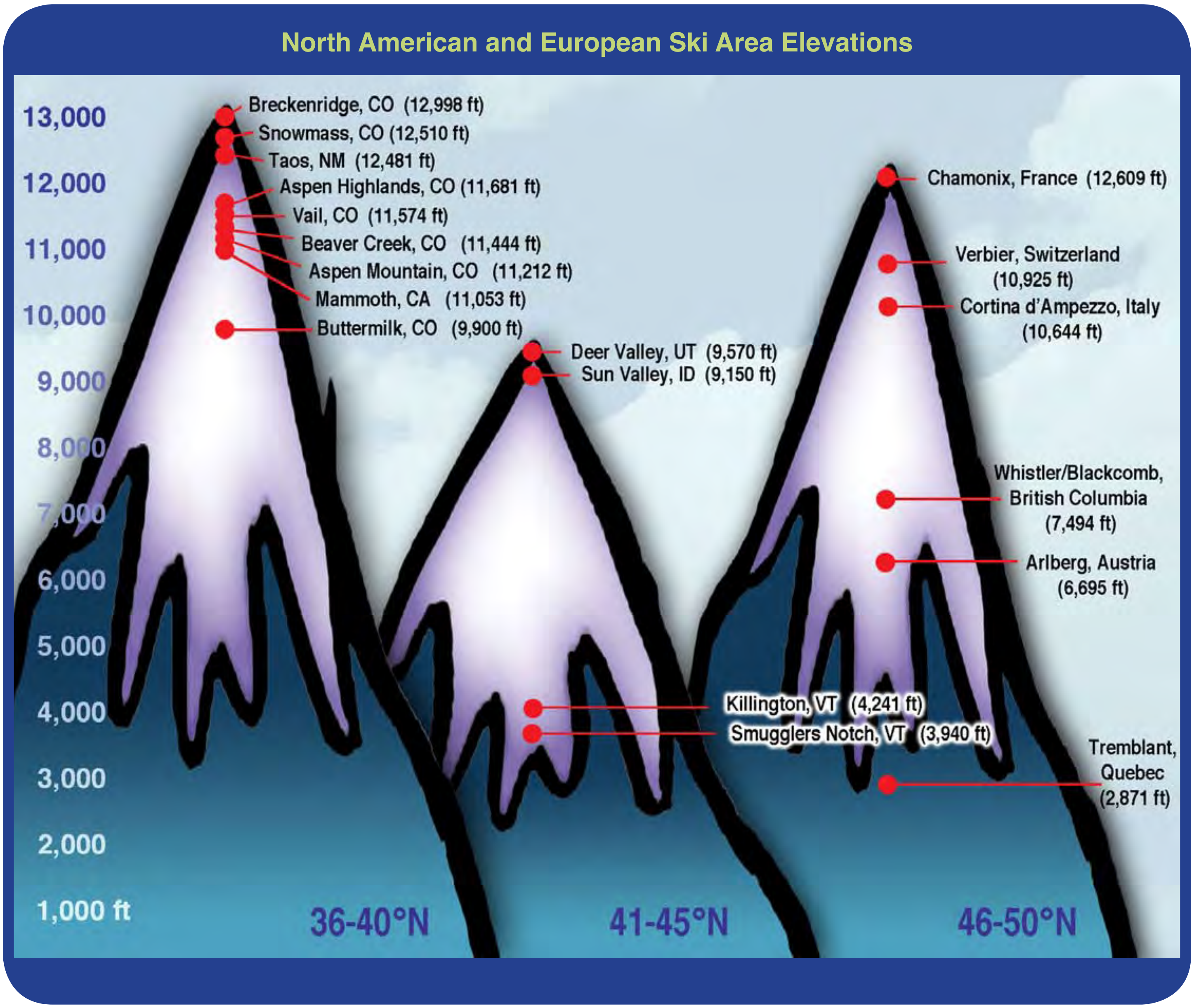


FIGURE 5.12: **North American and European ski areas sorted by top of mountain elevation and latitude.** Note: Ski resorts are additionally affected by atmospheric and ocean circulation patterns such as the North Atlantic Gulf Stream on European resorts.

to withstand a bad year or two. They also will enable ASC to proactively diversify its offerings to visitors, for example enhancing summer tourism opportunities on the mountains.

5.5.4 Potential Adaptations

ASC has several options for adapting to climate change, which are summarized in Table 5.15.

Strategies for Increasing Snow
Snowmaking will continue to be an important strategy, but adjustments to current operations may need to be made, like adding snowmaking capability to the top of Aspen Mountain and extending the snowmaking season. These two strategies will require more water, which may necessitate securing more water rights and expanding water storage capability.

Cloud seeding has been discussed in the past, but the expense, the uncertainty of its efficacy, and the environmental impacts make it a less desirable strategy.

Ski Industry Strategies for Adapting to Climate Change

- **Expand snowmaking to warmer temps** (less optimal due to increased costs/energy usage)
- **Expand snowmaking** to higher elevations
- Make and **stockpile more snow**; extend snowmaking into January; store it for mid-winter and spring use
- Attain more water rights, **build more water storage**

- **Adjust grooming techniques** to deal with decreased precipitation
- **More avalanche control**, build avalanche structures
- **Add higher ski terrain** (not at Aspen Mountain)

- Encourage skiers to **take advantage of optimal snow conditions by providing hourly ski reports**

- **Cloud seeding**
- **Download skiers**

- **Market the middle of the season**
- **Move World Cup and other pro races to later in season**

TABLE 5.15: **Ski industry strategies for adapting to climate change.**

Strategies for Improving Skier Experience
Given that later snow accumulation and earlier melting will make the base of the mountain unskiable more frequently, it may be necessary to expand the downloading capability. The gondola is one way to do this. Chairlifts can be designed to allow downloading as well.

Skiers may need to be encouraged to change their behavioral patterns: ski early in the morning, eat a late lunch, and download in the early afternoon when conditions become sub-par. They also may need to be encouraged to visit Aspen at different times of the year, a job for marketing.

Strategies for Limiting Damages Related to Climate Change
To mitigate the potentially damaging and disruptive effect of increased occurrences of wet slab avalanches in the spring, ASC may want to consider looking into the feasibility of placing avalanche control structures in areas prone to slides.

5.5.5 Costs and Constraints of Adaptation

Increased Snowmaking
The best hedge against the impacts of past climate variability on ski area operations has been snowmaking, and it will continue to play a central role as the climate warms, and snowpacks and ski areas around the world are affected. In a study of how current and improved snowmaking capacity might mitigate the vulnerability of the ski industry in southern Ontario (Canada) to climate variability and change, Scott et al. (2003) estimated that the amount of snowmaking required would increase from 36 to 144 percent in the 2020's, and from 48 to 187 percent in the 2080's. Even with adaptation through snowmaking, the study predicted that the average ski season

would be reduced by 0 to16 percent in the 2020's, 7 to 32 percent in the 2050's, and 11 to 50 percent in the 2080's.

ASC has an official climate policy, a proactive approach, that is a combination of mitigation of greenhouse gas emissions on the mountain and in its corporate operations. It also reaches beyond its local activities to carry its climate policy message to the media, industry, and policy arenas. Given the focus of this study on local climate change expressed mainly in snowpack changes, we only examined how Aspen Mountain managers might deal with climate variability and change in the future. We found that mountain managers were somewhat confident that they could adapt to most of the A1B scenarios we projected in 2030 and 2100 by adding snowmaking capacity to the top of the mountain, extending the snowmaking season by a few weeks, and opening a few weeks later if necessary. These adaptations would involve additional investments of money, energy, and water. The cost/benefit analysis for additional investments in snowmaking capability would, of course, have to be considered in light of ASC's overall climate response corporate strategy. Costs for ASC will rise as early-season nighttime temperatures rise, and snow must be made at less-than-optimal temperatures, requiring more energy to drive pumps and air compressors; however, the ASC decision to provide all of its electricity from renewable sources – announced in March of 2006 – decouples its snowmaking from carbon emissions.

Adding snowmaking at the top of Aspen Mountain would likely require an additional 5 millions gallons of water per season. At higher temperatures, the amount of water and energy required will further increase.

In a study of how climate change and reduced snowpack might affect Snowbowl, a ski area in Arizona, University of Arizona researchers Rosalind Bark-Hodgins and Bonnie Colby estimated that "variable costs of snowmaking in the Southwest are about $923 per acre-foot (af) (1,233 m^3) of snow, and it takes about 0.43 af of water to make one af of snow." In their study of how Snowbowl might adapt to climate change, they determined that: a 100 cm [39.4 in] snowpack decline at Snowbowl could contract its season 11 days, reduce visits by 7,348 and economic output by $0.91 million. Meanwhile making snow could become more costly; replacing all the snow with manmade snow would increase costs by $0.77 million and water use by 380 af. This leaves little room for snowmaking demands for a resort with an overall water supply of 486 af for snowmaking.

Indeed, the biggest costs and constraints related to increased snowmaking in Aspen, too, are likely to be associated with the need for more water and more water storage.

ASC currently gets water for snowmaking on its four mountains from several sources. Aspen Mountain gets treated water and Aspen Highlands untreated water directly from the city of Aspen. Snowmass Mountain relies on Snowmass Creek for its snowmaking, while Buttermilk Mountain obtains water diverted from Maroon Creek. Each of these strategies has its own set of costs and constraints, mostly related to environmental concerns. Here we focus on the costs and constraints related to expanding snowmaking operations at Aspen Mountain.

The City of Aspen guarantees ASC two million gallons per day (mgd) (7,570 m^3 per day)or in November and December, though in recent years ASC has used three mgd for a shorter, more intense usage period. In all, snowmaking at Aspen Mountain consumes approximately 45 to 50 million gallons (approximately 170,000 – 190,000 m^3) each winter. This number represents a significant reduction from the 65 million gallons (246,050 m^3) on average consumed in the years leading up to 1999, when ASC invested in the services of an outside consultant who helped operations managers identify ways to use less energy and less water to produce the same amount of snow. These energy-saving tactics had to do mostly with cutting back on snowmaking at higher temperatures. Adding snowmaking to the top of Aspen Mountain would likely require an additional 5 million gallons per season, which would still not bring total consumption back to pre-2000 levels. But if snowmakers are forced to turn on the machines at higher temperatures, the amount of water and energy required obviously will increase.

Important questions related to Aspen Mountain's water supply for snowmaking include: (1) How "senior" is ASC's claim to city of Aspen water? (2) What "junior" claims might be affected by the city's delivery of water to ASC under drought conditions? (3) Will the city have trouble meeting its current obligation to ASC under future climate conditions? (4) Will the city be able to accommodate additional demands for water from ASC for snowmaking at Aspen Mountain? (5) How secure is the city of Aspen's water supply? (6) Although it is beyond the scope of this report, which focuses on Aspen Mountain, what are the costs and constraints related to demand for increased water for snowmaking at ASC's other areas?

A review of the literature and conversations with stakeholders raise a number of concerns about the environmental impacts related to snowmaking, including the dewatering of streams during already low-flow periods, and other concerns related to alteration of the hydrologic cycle, such as increased runoff in the spring, which can cause excessive channel erosion.

Withdrawing water from streams in November and December prolongs normal late-summer low flows for months, and leaves streambeds and aquatic communities, like the prized trout fisheries in Aspen, more exposed and vulnerable to cold temperatures and freezing and drying. Anchor ice, which forms in shallow water, adheres to stream bottoms affecting egg viability and essentially rendering the body of water uninhabitable. And with dewatering there are fewer deep pools for fish to overwinter. The absence of flushing flows can lead to sedimentation and problems related to algal growth.

Constraints

ASC has had to deal with these concerns on several occasions over the last decade as they have sought to expand operations at both Snowmass and Aspen Highlands. ASC's ability to expand snowmaking hinges not just on its paper water rights and the city's water commitment, but on its special use permit with the White River National Forest (WRNF). The legal and public relations challenges ASC encountered in the 1990's have relevance for future challenges it is likely to face related to snowmaking.

In the early 1990s, during the planning for the expansion of Snowmass, ASC had to address stakeholders who were concerned about plans for increased snowmaking. Snowmass Water and Sanitation District's (SWSD) withdrawal of water from Snowmass Creek has long been controversial largely because it withdraws water from one basin (Snowmass Creek) and moves it to another for use (Brush Creek). The SWSD determined it would need five cfs of water in November and December for additional snowmaking. The Colorado Water Conservation Board (CWCB) established minimum streamflows for Snowmass Creek using a state-of-the-art "stairstep" approach. Some stakeholders still wonder if the revised minimum instream flow thresholds are adequate to sustain the creek's aquatic ecosystem, especially given SWSD's status as senior water rights holder on Snowmass Creek, and its right to legally withdraw water even when the Creek is running below minimum streamflows.

> Early season skiing is vulnerable to increased temperatures that delay the build-up of natural snow, and reduce the potential for snowmaking.

Later in the 1990s, with the planned expansion of Aspen Highlands, ASC had to address similar concerns related to snowmaking impacts on Maroon Creek and went through an EIS process with WRNF. The Final Record of Decision (ROD) issued in 1997 allowed ASC to develop and apply snowmaking to 124 acres (0.5 km^2), an increase of 48 acres (0.2 km^2) over the previously existing situation. This was considered to be "the very minimum that would be needed to allow the skiing public to egress the mountain during a dry weather cycle." In recognition of concerns about the dewatering of Maroon Creek, the USFS established a minimum flow of 22 cubic feet per second (cfs) (0.6 cubic meters per second [m^3s^{-1}]) "to protect aquatic life." This minimum flow goes above and beyond the 14 cfs (0.4 m^3s^{-1}) instream flow requirement on Maroon Creek established by the Colorado Water Conservation Board (CWCB). These instream flow requirements are senior to ASC's water rights filings.[26] Because of the concerns about extending low-flow conditions into the winter, the ROD states that snowmaking must be completed by December 31. The ROD concludes that "while the reduction in streamflows in Maroon Creek would reduce spawning habitat, this reduction would not threaten the sustainability of the Roaring Fork fish populations which spawn in Maroon Creek."

Also at issue are the legal requirements surrounding the four endangered native fish species in the Upper Colorado River, into which Maroon Creek, via the Roaring Fork River, flows. The ROD reports that consultations with the U.S. Fish and Wildlife Service (USFWS) determined that the proposed water depletions for snowmaking at Aspen Highlands would be small enough (< 100 acre feet [123,348 m^3]) that the already established Recovery and Implementation Program for Endangered Fish Species in the Upper Colorado River Basin would be a "reasonable and prudent alternative" to avoid the jeopardy to these fishes or their critical habitat brought on by the depletions.

In sum, there appears to be a lot of concern about snowmaking not just among Aspen stakeholders and environmental groups, but among USFS and State Engineer's Office personnel as well. These findings raise several questions related to constraints on ASC's ability to adapt through snowmaking: (1) How strong is the WRNF's authority to condition ASC's special use permit and potentially limit snowmaking operations? (2) How likely is the WRNF to exercise such authority? (3) What other legal mechanisms might be triggered by ASC's plans to divert more water for snowmaking, e.g. those related to endangered fish in the Upper Colorado?

In regard to the city of Aspen's water supply, local vulnerabilities seem to focus on capacity in relation to future growth/demand

26. ASC's water rights filings for snowmaking at Aspen Highlands are for 58 acre feet (af) (71,542 m^3) of water, which equates to a consumptive use of 15 af (18502 m^3) and are under the name "Hines Highlands Limited Partnership and Aspen Highlands Mountain Limited Liability Company."

and extended droughts and how they test the system's capacity. Big picture vulnerabilities are threats from increased demand on the Front Range, particularly for municipal use and, to the west, the strained Colorado River system with a complex set of state and federal issues.

ASC's Environmental Affairs Coordinator Auden Schendler is confident that the corporation will find solutions to the water problem: "As one of the drivers of the growth leading to increased demand for water, Aspen Skiing Company will lead in the pursuit of solutions."

5.5.6 Vulnerabilities Summary

Performance of the ski industry is closely linked to climate, though the industry has sought to make adjustments, like snowmaking, that have lessened the tightness of that link. Moreover, as "skiing" evolved into a more complex behavior that included everything from high-end shopping to other snow sports (e.g., tubing and sleigh rides; and terrain parks not as subject to natural snow conditions) to real estate investment and development, the industry's position of living or dying based on snowfall has been mitigated. Communities like Aspen, to which skiing is central, have also benefited from this diversification of the sport and its associated tourist economy.

Yet, ski conditions per se remain sensitive to climate. Snowmaking is effective for only part of the year, and for only part of the mountain. Moreover, the sensitivity is not just to snowfall, but to temperatures. Indeed, we found temperature to be as important as precipitation, and possibly more so. While natural snow is needed to open the mountain, snowmaking is also critical, and quite sensitive to temperature. Without significant adjustment, Aspen Mountain may lose a week of skiing on both ends of the winter season. If this contraction of the season continues past 2030, then risk of losing a week or so during the important "spring break" period may become a bigger concern than a late start to the season.

Spring conditions, and closing dates, are especially sensitive to temperature. And it so happens that one of the most robust expectations associated with global warming is that temperatures will increase even if precipitation does not change. Early season skiing (before mid-Jan.) is vulnerable to increased temperatures that delay the build-up of natural snow, and reduce the potential for snowmaking.

Snow conditions through the season are also important, in both direct (the skier's experience) and indirect ways (perception of conditions by potential customers). Poor early season conditions may affect perceptions and vacation planning, affecting skier days later in the season as well as overall skier days. Quality of skiing is difficult to discern from snow modeling, but projected delays in accumulation imply problems establishing good conditions by the critical Christmas/New Years period.

Despite these potential impacts, we found Aspen mountain managers relatively optimistic that they could adjust to, and work around, the conditions that might adhere to a typical year circa 2030. They already have experience dealing with warmer, drier years, and have developed flexibilities of infrastructure management (e.g., opening and closing trails), snowmaking, and snow grooming, all to provide a reliable, quality skiing experience. Certainly there are money and water constraints, but the first approximation is that 2030 conditions do not mean the "end of skiing."

A few additional concerns are worth raising here. This study focused on "average" conditions, or at least those as represented by a recent typical year (2000-01). Climate change can also occur as changes in the frequency of extremes, or of certain threshold conditions. It may not make much difference to ski managers if every winter in the 2030s is a bit warmer, but it may matter greatly if, say, three or four winters during the 2030s are extremely warm. Two very poor seasons in a row could establish new, negative skier perceptions. Future assessments must pay more attention to the frequency of future conditions. Might future decades offer more early seasons like 1999 and late seasons like 2004? And is there a tipping point where skier days become more closely connected to climate again? The study team suspects this point is beyond 2030, but is certainly before 2100.

> **By 2030, the economic consequences of a delayed season or poor conditions could range from losses of $16 to $56 million.**

5.6 INDIRECT ECONOMIC IMPACTS OF CLIMATE CHANGE

Intuitively, we know that effects of significant climate change will propagate beyond the direct impacts on skiing. We suggested in the Visitation Sensitivity Matrix (Table 5.8) that several sectors may be indirectly affected by change in visitation or by increasing or decreasing snowfall.

The linkages between direct and indirect base industries in resort economies are not well understood, though some of the state's top economists have begun working to better trace these linkages. The same characteristics that make indirect industries difficult to track make them less sensitive to fluctuations in any single sector. Many indirect industries have a broad client base that extends beyond the visitor-based sector in Pitkin County (accountants, lending institutions, business supply, business services, etc.), and many activities associated with the growing economy of the Aspen-to-Rifle corridor (e.g., transportation services) are not closely linked to ski tourism or to climate. This diversity makes it unlikely that the indirect industries would decline and increase proportionate to the visitor-driven fluctuations in the direct base activities discussed earlier. We estimate that 23 percent of the economic base is associated with indirect activities that have some links to tourism, and thus are at least indirectly sensitive to climate-induced changes in visitation and spending. But we simply have no way of estimating this effect at this time. The question circles back to a common conundrum of resort economics and planning: how much of the non-recreation economy, the professional services firms, consultants, etc., is tied to resort qualities? Surely some of what goes on in Aspen's professional sector happens there (say, instead of in Grand Junction) because of its rich combination of outdoor and cultural features, but we do not know how much. It is reasonable to say, though, that these sectors are not especially sensitive to modest changes in climate or even to ski season length.

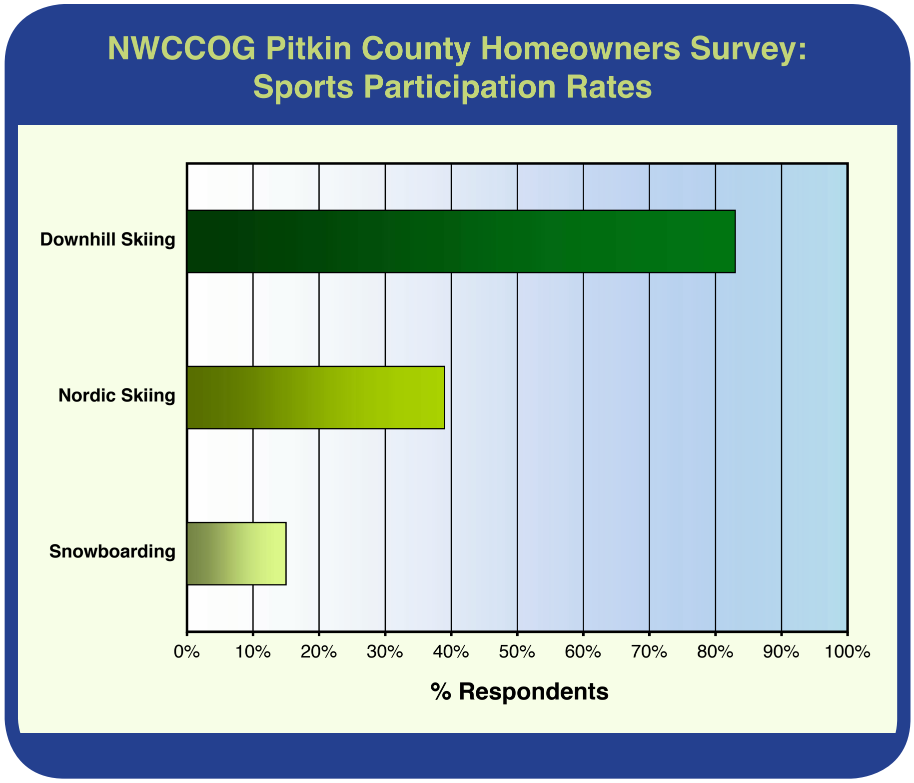


FIGURE 5.13: **NWCCOG Pitkin County Homeowners Survey, sports participation rates.**

Yet logic also dictates that some indirect, and non-skiing sectors of the local economy, are indeed sensitive to climate. A significant residential sector in Aspen (and other resorts) is comprised of second homes, and a growing cohort of retirees and other so-called "amenity migrants" who invest in Aspen real estate and spend money in the local economy. There is some reason to expect that changes in temperature, snowfall, and snow quality would affect this sector. Recent survey work by the Northwest Colorado Council of Governments revealed the importance of climate, winter activities, and recreational amenities to homeowners of all types (Figure 5.13 and 5.14).

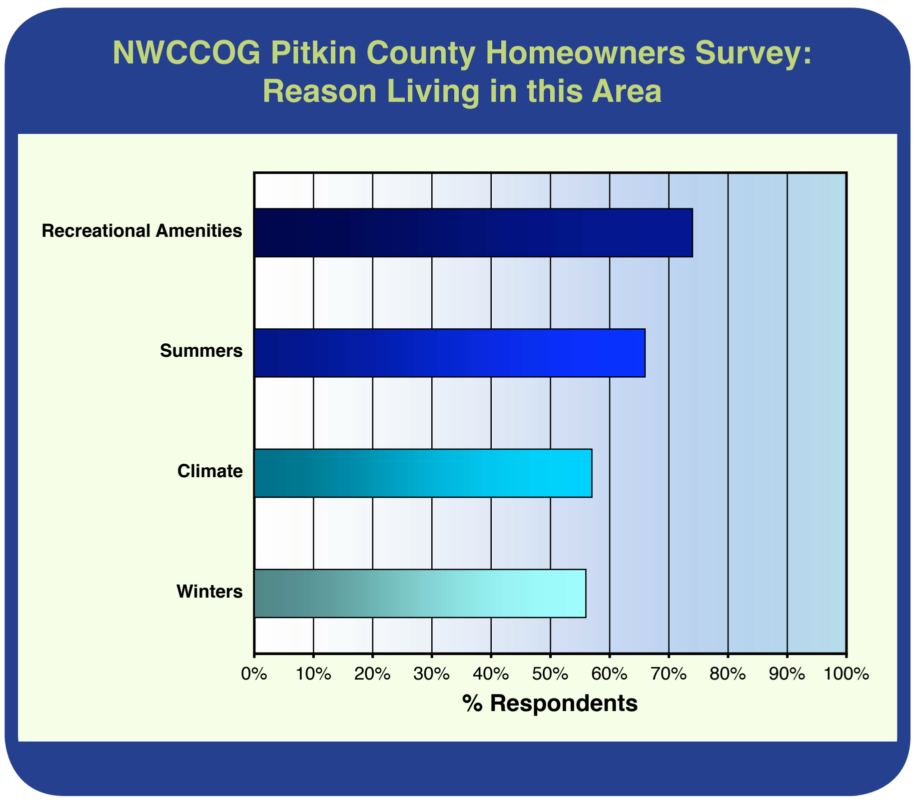


FIGURE 5.14: **NWCCOG Pitkin County Homeowners Survey, reason living in this area.**

While it is clear that these amenities are important to homeowners in the survey, which included second home owners and full-time residents, it is less clear how a change in the quality or quantity of any single amenity would change consumer decisions. We can surmise that a degradation of winter recreation would hurt this sector. One pathway is via investor's first introduction to the area. Between 1998 and 2000, the Pitkin County Community Development Department conducted three separate studies detailing the role that residential development and occupancy play in the regional economy. Most of the residents interviewed during this original study (and during a subsequent study: Post-Construction Residential Workforce Dynamics) traced their original interest in the Aspen area to a ski trip. In many cases, the initial second home purchased was a ski condo, eventually to be traded up for a town home, detached house, and rural property. The percentage of survey respondents gave "Recreational Amenities" (nearly 80%) and "Proximity to a Ski Resort" (about 75%) as a reason they bought a home, while over 40 percent of the survey respondents gave climate as a reason. It is possible that a fluctuation in visitation, particularly a significant downturn, could have a delayed effect on the demand for second homes simply because a greater or lesser number of prospective buyers are exposed to the area.

> The maintenance of skiing as a central component of Aspen's culture and economy in the face of regional climate warming may involve significant economic investment and environmental costs.

But it is also worth noting that slightly more respondents in the NWCCOG study rated summers rather than winters as a reason for living in the area. Since part of the attraction of summer is the cooler Rocky Mountain climate, it is reasonable to expect that warmer summers would reduce the quality of their experience. Both winter and summer impacts on this sector would have to be analyzed in comparison to other areas where owners might invest. Second homes are an important part of the economy of areas further south than Aspen (e.g., Santa Fe, Taos), and of much warmer climates (e.g., the desert golf resorts). Moreover, as one realtor said to us in interviews for this project, warmer weather in Aspen is not a problem as long as it also gets warmer in places like Texas. A warmer climate might enlarge the summer season, opening up the shoulder periods in spring and fall to summer activities like golf and festivals, lengthening the construction season, and perhaps reducing the cost of construction in the area.

5.7 CONCLUSIONS

A typical ski season in Aspen around the year 2030 is likely to be a week shorter, mostly because of later starts associated with both delayed snowmaking and delayed accumulation of natural snow on higher slopes. Closing day in spring is less sensitive because Aspen areas (and other Rocky Mountain ski areas) often close with sufficient snow to stay open longer if demand and economics dictate. But maintaining desirable ski conditions in warmer spring weather, and managing the melting lower slopes and avalanche-prone areas, will require more effort. Climate warming effects are much more pronounced by 2100 when the ski season could start anywhere from 1.5 to 4.5 weeks later, and significant melting begins 2.5 to 5 weeks earlier. It is also likely that the lower slopes will have no permanent natural snowcover by 2100 (in a sense, the base areas could become, climatologically, more like Carbondale or even Glenwood Springs).

It seems feasible that ski managers can compensate for the 2030 conditions by intensified snow management and snowmaking, though there are some constraints to expanded snowmaking, as described above. The 2100 scenarios are more dire, with the loss of a month or more of skiable conditions, and loss of reliable natural snow cover on lower elevation slopes (which might be compensated for by snowmaking). We have focused here on the closer, 2030 scenario for a variety of reasons, but it does appear that sometime between 2030 and 2100, Aspen's climate will work against its reputation as a destination ski resort.

The 2030 scenarios may or may not mean fewer skiers in the course of a season. Early season skiers may simply show up later (the historical record since the 1970s includes poor years that actually enticed above-average skier turnout). The scenarios do imply greater costs and effort in terms of mountain and visitor management. If season delay or poor conditions do shave 5 to 20 percent off of skier numbers by 2030, then the economic consequences could be significant, ranging from losses of $16m to $56m in total personal income (in today's dollars). For this study, we were not able to estimate the impacts on individual businesses or on ASC. Though it cannot be reliably quantified, poorer ski conditions are likely to affect the resort real estate market in Aspen, thus adding to losses. This might be off-set somewhat by a longer summer season. Interest in Aspen during the summer, and in Aspen real estate, is not necessarily tied to ski conditions.

These scenarios speak to average conditions, but actual years come and go as individual ski seasons with more or less troublesome conditions, like late snowfall, inconsistent mid-winter conditions, and early melt. The probability of these conditions will increase over time as the global climate warms. Change may occur gradually, in almost a linear fashion between now, 2030, and 2100, or it might manifest as step-like changes and clumps of bad years. If ski towns are unlucky, global warming will manifest itself as more frequent very poor years that become newsworthy, or, worse, as runs of several poor years in a row that fundamentally change skier perception and behavior. These runs of poor years may well be balanced by runs of good, even great, years, but nonetheless each bad spell will incur significant economic and social effects. In a climate changing in a unidirectional manner, these effects would eventually pass some threshold at which assured, high-quality, destination skiing becomes untenable. It would appear from this analysis that this point is sometime after 2030, but before 2100.

The maintenance of skiing as a central component of Aspen's culture and economy in the face of regional climate warming may involve significant economic investment and environmental costs. Increased snowmaking and adaptive snow and slope management can mitigate the average conditions of 2030 (though we do not diagnose the potential effects of individual years, or runs of poor years, which could change the perception of Aspen as a destination resort). But, by 2100 it seems doubtful that assured, high-quality, destination skiing can be maintained as Aspen's winter raison d'etre. Similarly, the many features that make Aspen an attractive summer resort, including its Rocky Mountain small town setting and mountain climate, would appear little affected by climate change in the next couple of decades, but the longer term prospects, in the face of warming summers, are less clear.

6. ROARING FORK RIVER STREAMFLOW: IMPACTS, ADAPTATION, & VULNERABILITIES

6.1 INTRODUCTION

This chapter is the result of work added to the project after the work represented in Chapter 1 through 5 was completed. The additional work was made possible by support from the Environmental Protection Agency and was produced by Stratus Consulting and the Aspen Global Change Institute as deliverables under contract to TN & Associates, for contract WA3-1, "Climate Impacts and Adaptation Opportunities for Surface Water Resources in the Roaring Fork Watershed." The first, section (6.2), models snowmelt runoff in the upper Roaring Fork River to the confluence with Woody Creek. The modeling examines runoff with the main climate scenarios described in Chapter 2; Section 6.3 describes uses, rights, diversions, and impacts from a historical perspective, and; Section 6.4 describes the approach and results of interviews with stakeholders representing physical appropriators and in-stream users. The stakeholder interviews explored how climate change (in the form of different runoff patterns) could affect those uses.

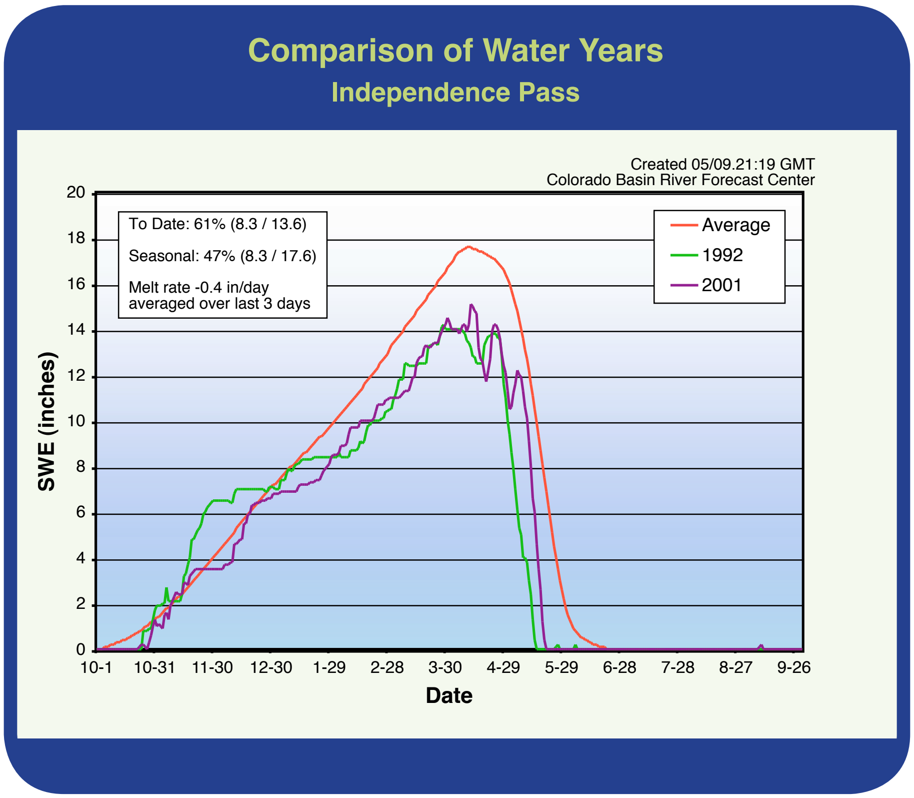


FIGURE 6.1: **A comparison of water years for 1992 , 2001, and the historical average from 1981 to 2005.** (Source: Data is from the Independence Pass SNOTEL site (IDCP2). NOAA/CBRFC, 2006 (http://www.cbrfc.noaa.gov/snow/station/sweplot/sweplot.cgi?IDPC2?avg.1992.2001??0???0?s))

6.2 RUNOFF MODELING FOR THE UPPER ROARING FORK RIVER

We developed and applied a snowmelt runoff model to analyze how streamflow in the Roaring Fork River at the Woody Creek confluence might change under the future climate scenarios selected for analysis in this report (see climate modeling, chapter 2). This assessment of streamflows builds on the analysis of snowpack conditions on Aspen Mountain, which is also included in this report (see snowpack analysis, chapter 3). The snowpack analysis focused on estimating winter (October through March) snowpack conditions on Aspen Mountain. The snowmelt runoff analysis was designed to provide insight into the annual runoff patterns, such as the timing of peak flows and relative changes in average monthly streamflow.

Runoff modeling results show that, based on the simulations for the A1B emission scenario natural streamflow in the Roaring Fork River in the year 2030 should retain its characteristicpattern of low winter flow with late spring to summer peak flow, although peak flow is predicted to shift from June to May in 2030. Predictions for the year 2100, under the B1, A1B, and A1FI emission scenarios, also indicate that peak flow will shift from June to May. However, increased winter flow is predicted due to a mid-winter melt that does not occur under current conditions, with a corresponding reduction in early summer flow due to a depleted snowpack. These results and the methods used to derive them are discussed in more detail below.

6.2.1 Methods

Stratus Consulting used the Snowmelt Runoff Model (SRM), developed and maintained by the U.S. Department of Agriculture's Agricultural Research Service (Martinec, 1975; Martinec et al., 1994; http://hydrolab.arsusda.gov/cgi-bin/srmhome), to estimate runoff volume and timing in the Roaring Fork River at the Woody Creek confluence under selected future climate scenarios. The SRM simulates surface processes, and is specifically designed to assess snow coverage and snowmelt runoff patterns. The SRM uses a temperature-index method, which is based on the concept that changes in air temperature provide an index for snowmelt.

Using the SRM, we simulated runoff in the 2001 water year (the 12 month period from October through September) for calibration purposes. Model inputs were daily temperature, precipitation, and snow covered area data from 2001. The 2001 water year was originally selected for the Aspen snowpack study because it is representative of average winter (October through March) snowpack conditions on Aspen Mountain, and not because of its annual precipitation or streamflow characteristics. Streamflow in the Roaring Fork River is influenced by upstream diversions, dams, and withdrawals, and thus may not completely reflect natural changes in streamflow due to runoff. We therefore used simulated average monthly streamflow instead of measured streamflow to calibrate the snowmelt model. To calibrate the runoff model for the 2001 water year, modeled average monthly natural streamflows in the Roaring Fork River at the Woody Creek confluence were obtained from a watershed modeling study conducted by the Colorado Water Conservation Board (CWCB, 2006). The modeled natural streamflows are only available for the years 1909 through 1996. Snow covered area analysis results, as dictated by the Aspen snowpack study, were only available for 2001. We therefore selected 1992 as a surrogate calibration water year for 2001 because it was the year that most closely resembled the annual snow water equivalent accumulation and depletion at the Independence Pass SNOTEL site (Figure 6.1). Also, streamflow measured in the Roaring Fork River above Aspen was similar during that year.

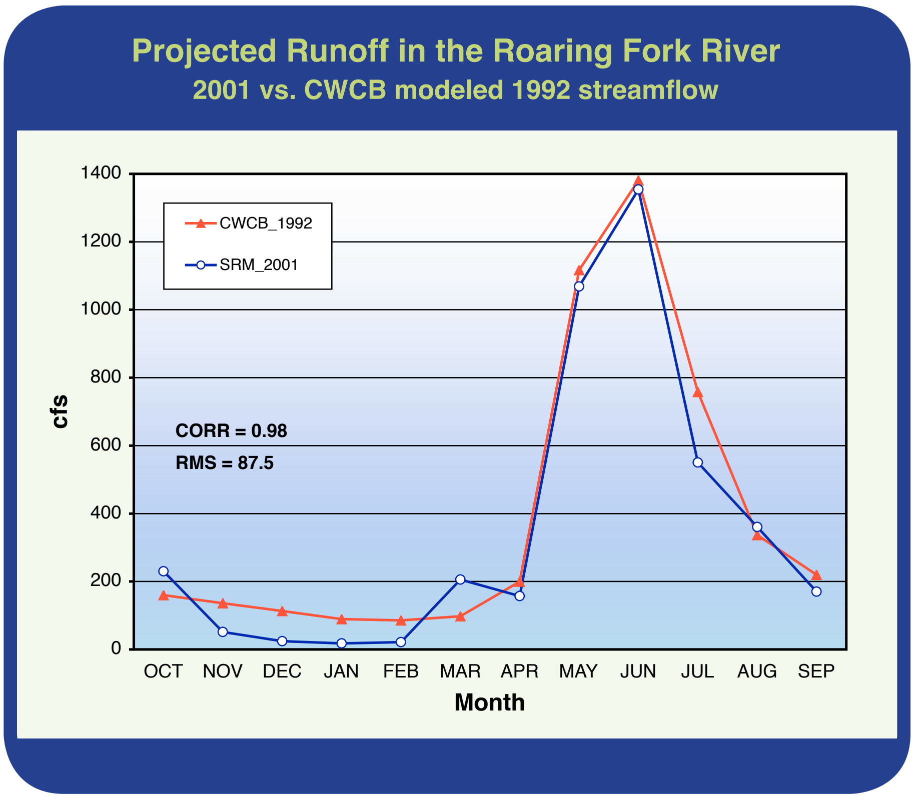


FIGURE 6.2: **Projected runoff in the Roaring Fork River at the Woody Creek confluence for 2001 versus CWCB modeled 1992 streamflow.** Note: SRM flows do not include base flow.

Model calibration was conducted by first calculating the 2001 water year, monthly average runoff from daily estimates generated by the SRM, then comparing those to the simulated 1992 natural streamflows. The SRM code simulates runoff only, and does not estimate streamflow contributions from groundwater (i.e., base flow). We adjusted the runoff model parameters using the correlation coefficient and root mean square difference between the model output and the data, to determine best fit. We achieved a correlation coefficient of 0.98, and a root mean square error value of 87 cubic feet per second (cfs) (2.5 cubic meters per second [m^3s^{-1}]) (Figure 6.2), compared to an average peak streamflow of approximately 1980 cfs (56 m^3s^{-1}).

It should be noted that the predicted natural streamflows (CWCB, 2006) include both runoff and base flow. However, base flow is only a small component of the total annual flow in the Roaring Fork at the Woody Creek confluence. We estimated base flow to be less than 5% of peak flow from graphs of predicted natural streamflow from the CWCB 2006 modeling study. Thus, runoff predictions could be compared directly to predicted natural streamflows without introducing significant error.

Once the model was calibrated to the 1992 streamflow data, we simulated runoff using selected climate models and emission scenarios for the years 2030 and 2100 by scaling observed temperature and precipitation records by the changes in the various scenarios. We applied the monthly changes in temperature and precipitation from the climate scenarios to each day of the month in the daily data series for 2001.

The climate scenarios span a range of different estimates of greenhouse gas emissions and climate sensitivity, and produce a range of potential regional changes in temperature and precipitation. We used the same climate scenarios as those used in the snowpack analysis. As is summarized in Chapter 2, Table 1 of this report, those scenarios include increases in temperature in both 2030 and 2100, with a greater increase in 2100. Average precipitation is predicted to decrease in both 2030 and 2100, with the decrease being greater in 2030 than in 2100, although there is high variance amongst the climate models. For the year 2030, we simulated runoff using the wettest and driest climate model predictions for the A1B emissions scenario, as well as the average of all the climate models. There is very little divergence between the emissions scenarios by 2030, so we consider the A1B scenario to be indicative of the other emission scenarios. For 2100, we simulated runoff using the average of all the climate models for emissions scenarios B1, A1B, and A1FI.

6.2.2 Results

The 2030 runoff modeling predicts that the general seasonal pattern from the simulated 2001 data is shifted to an earlier peak runoff, but most significant snowmelt doesn't occur until April as is historical. (Figure 6.3). The historical seasonal pattern of low winter flow with a later spring to early summer peak flow is retained under all climate models for 2030. Therefore, temperatures used as input to the runoff modeling for 2030 are not warm enough to cause mid-winter melting of the snowpack, and the seasonal pattern is dominated by the late spring-early summer melt of the winter snowpack.

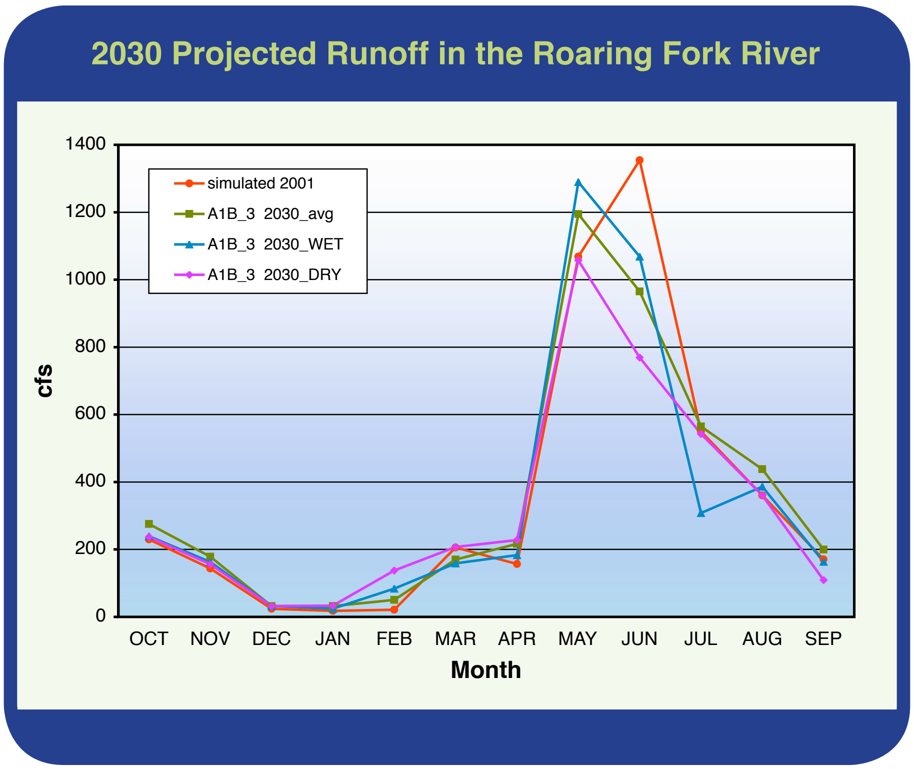


FIGURE 6.3: **Projected runoff in the Roaring Fork River at the Woody Creek confluence for 2030 for for the wettest, driest, and average of the five climate models under the A1B (medium emissions) scenario, for 5.4°F (3°C) sensitivity.** Note: These flows do not include base flow.

However, in the year 2030, peak runoff is predicted to occur in May rather than June (Figure 6.3). Since runoff is estimated in the model on a monthly basis, it is not possible to determine how many days or weeks earlier the runoff would occur. Although the SRM code does predict flows on a daily basis, only monthly natural streamflow predictions (CWCB, 2006) were available for calibration of the runoff model. Thus, the runoff model predictions can only be made monthly with confidence, at the same temporal resolution as the calibration dataset. Based on visual examination of the projected runoff output, the shift in peak runoff could be somewhat less than a month.

Changes in total annual runoff volume in 2030 reflect the climate scenario predictions regarding decreases in annual precipitation. Under the A1B average and wet scenarios, total annual runoff volume in 2030 is predicted to be approximately 0 to 5% less than runoff volume in 2001. Under the dry scenario, total annual runoff in 2030 is predicted to be approximately 10% less than runoff volume in 2001.

In 2100, the seasonal pattern of runoff is predicted to be dramatically different than the seasonal pattern observed in 2001 and that predicted for 2030 (Figure 6.4). As in 2030, the timing of peak runoff is predicted to shift from June to May, but the more substantial warming in 2100 will result in increased winter flow caused by mid-winter melt, particularly in February. This mid-winter melt subsequently will cause a corresponding reduction in June flows because the winter snowpack will no longer exist in June. The rebound in total runoff volume in July will be the result of summer monsoons predicted by the climate models in 2100. Therefore, by 2100, the historic runoff seasonal pattern will be substantially altered. Not only will the timing of peak runoff shift, but the pattern of low mid- to late winter flow will no longer be evident.

Under all climate scenarios, the total annual runoff volume in 2100 is predicted to be approximately 5 to 15% greater than in 2001, and slightly greater than predicted for 2030. These differences are a result of the monthly patterns of change in precipitation predicted for the year 2100 versus

2030, combined with the seasonally varying estimated losses of precipitation to infiltration and evaporation. Total annual runoff volumes are dictated by actual monthly runoff volumes, which account for precipitation losses to infiltration and evaporation. An increase in precipitation during months with low losses, and a decrease in precipitation during months with high losses, or a combination of both, could result in a scenario with decreased total annual precipitation but increased total annual runoff volume.

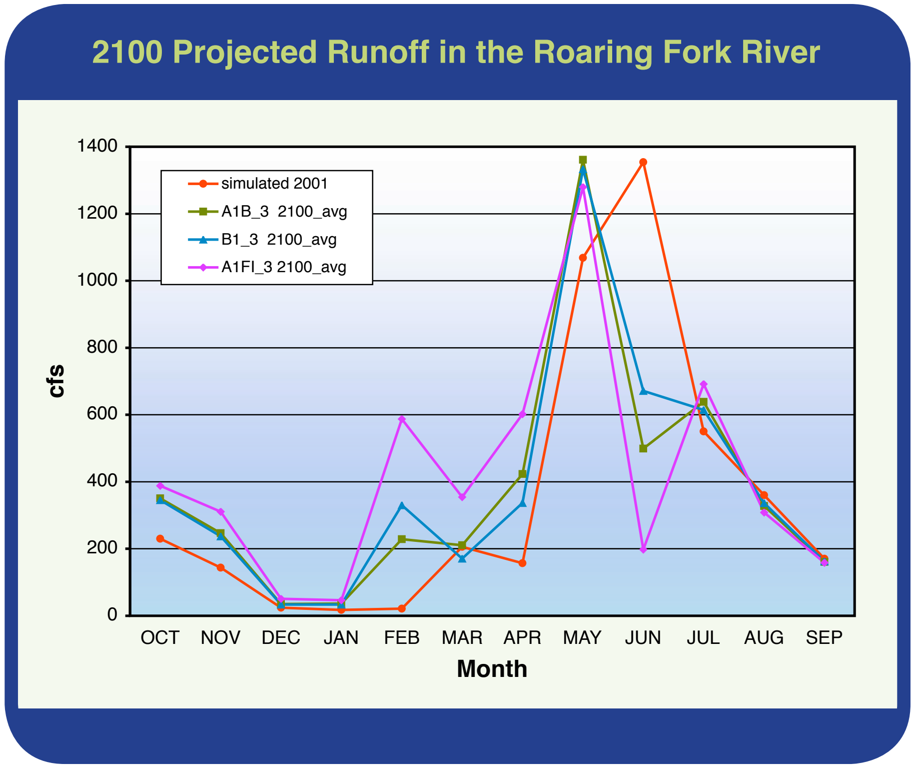


FIGURE 6.4: **Projected runoff in the Roaring Fork River at the Woody Creek confluence for 2100 under the A1B (medium), B1 (low), and A1FI (high) emissions scenarios for the average of the five climate models.** Note: These flows do not include base flow.

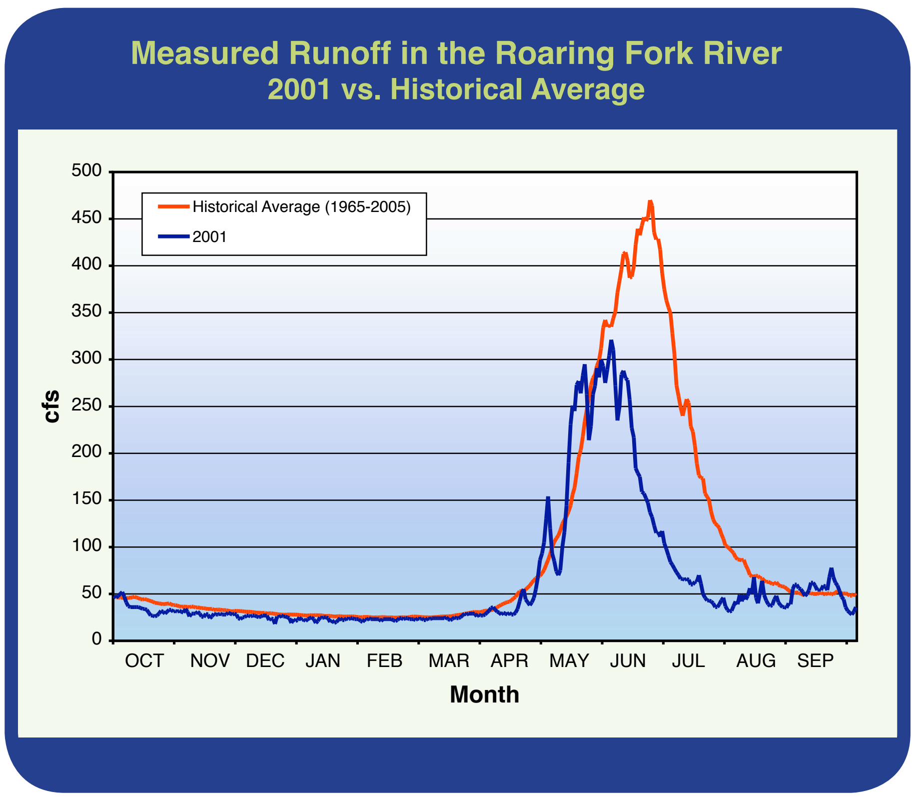


FIGURE 6.5: **Measured runoff in the Roaring Fork River above Aspen for 2001 and the forty year historical average. Note: These are flows altered by the Twin Lakes Diversion.**

6.2.3 Model Uncertainty

Although the winter (Oct. through Mar.) snowpack conditions on Aspen Mountain for the 2000-2001 ski season were representative of the historical average from 1965-2005 average measured 2001 streamflows, throughout the melt season (May through July), were lower than the historical average observed streamflows. The observed streamflows in Figure 6.5 are altered by the upstream Twin Lakes Diversion. During the melt season this is a significant diversion. Historically the diversions for May, June, and July are 51.5%, 32.2%, and 30.9% respectively of pre-altered simulated flow (Clarke, 2006). While monthly average streamflow for 2001 is representative of the historical average through April, it is well below average for May through July. 2001 was a suitably representative year for winter snow depths on Aspen Mountain and was a typical year for total precipitation measured at the Independence Snotel station and was included in this study for these reasons.

Changes in annual average precipitation result in changes in total annual runoff volume. Changes in monthly temperatures alter the timing and monthly runoff patterns in the annual hydrograph (a graph that charts change in discharge of a stream over time). The climate models all show an increase in annual average temperature in 2030 and 2100, with low variance among the climate models, and greater warming in 2100. In contrast, the climate model averages show a decrease in annual precipitation in 2030 and 2100 compared to 2001, but the climate models exhibit high variability between the models, implying a higher degree of uncertainty in the precipitation projections. Annual precipitation changes are projected to be fairly minor, and given the high variance between the climate models, we are uncertain how precipitation will change in the future.

Calibrating the runoff model for 1992 to 2001 modeled natural streamflow data introduces uncertainty in determining the effectiveness of the calibration procedure. While there is not likely to be substantial changes in annual runoff for the chosen scenarios, the uncertainty in precipitation projections, combined with the uncertainty in the calibration procedure, cause us to have low confidence regarding the direction of possible change in total annual precipitation or total annual runoff volumes. We therefore have confidence in the timing of monthly runoff patterns but not in total annual runoff volumes.

6.3 WATER USE AND POTENTIAL CLIMATE CHANGE IMPACTS IN THE UPPER ROARING FORK BASIN

The preceding section presents potential impacts of climate change on runoff patterns in the upper Roaring Fork River. Those changes in runoff will affect various river uses in a variety of ways. The following discussion outlines the current uses of the river, and then briefly describes potential impacts from changes in runoff patterns on those uses.

In the year 2030, peak runoff is predicted to occur in May rather than June.

6.3.1 Summary of Upper Roaring Fork River Usage

Municipal Water Use

The major municipal user in the upper Roaring Fork River is the city of Aspen. The city of Aspen's municipal water supply is captured from both surface water and groundwater supplies. The majority of potable water supplies for the city are diverted at intake facilities on Castle Creek and Maroon Creeks. However, not all potable demand can be satisfied via Castle and Maroon Creeks. Therefore, the city also utilizes wells drilled into the alluvial groundwater aquifer adjacent to the city (Enartech, 1994). The aquifer, which supplies 5 to 30% of Aspen's potable water, is hydrologically connected to the surface waters of the Roaring Fork and relies on periodic flooding for recharge (Hartman, 2004).

The city also diverts untreated water for irrigation through multiple ditch facilities located on the Roaring Fork River and Castle and Maroon Creeks. The city uses the non-potable water for irrigation of open space areas, parks, and golf courses (Enartech, 1994).

Municipal water use in the upper Roaring Fork River is significant. Total daily demand by municipal system residents is 161 gallons per day (gpd). While the city can produce up to 20 million gallons daily, 1.4 billion gallons of treated surface water annually, and has a total storage capacity of 9.66 million gallons, it is not immune from demand shortages (City of Aspen and Pitkin County, 2006). Demand forecasting and model simulation in a 1994 study prepared for the City of Aspen Department of Utilities concluded that the likelihood of water shortages in the city was 13%-40%, depending on the scenario (Enartech, 1994).

The population within the Roaring Fork watershed has been growing because of numerous outdoor recreational opportunities (angling, golfing, skiing), and a rural lifestyle with urban amenities (Hempel and Crandall, 2001). According to the Roaring Fork Watershed Inventory conducted in 2003, there were 14,472 people in Pitkin County in 2000 and 5,914 people in the municipal Aspen area (O'Keefe and Hoffmann, 2003).[27] The county experienced a 12% growth in population from 1990-2000 (Aspen Chamber of Commerce, 2006). In response to increasing populations, Aspen drafted the Year 2000 Aspen Area Community Plan, which placed growth quotas on all aspects of growth, with the exception of affordable housing (a continual problem in portions of the valley). The plan stipulated that growth should be limited to less than 2% per year (City of Aspen, 2000). Based on the data from 1998, a maximum population for the area around Aspen is estimated at 28,000 to 30,000 (City of Aspen, 2000). However, even with controlled growth, municipal services will need to continue to expand, and the potential for water shortages may increase.

A study conducted in 1994 for the city of Aspen showed that while water availability is typically greater than combined potable demands, irrigation demands, and instream flow demands, shortages will increase with growth, especially during base flow periods (winter months) following dry years (Enartech, 1994). Much of the increased water demand for the city of Aspen will be satisfied through increased withdrawals from the alluvial aquifer (Enartech, 1994). Pumping from the city's existing alluvial wells already reduces streamflow of the Roaring Fork as it flows through town. Though the city's impact on the Roaring Fork's flow is relatively minor, the impact of increased well pumping from the alluvial aquifer would most likely result in flows below instream flow designations (32 cfs [0.9 m^3s^{-1}]) for about 9 months out of the year (Enartech, 1997).

27. A study completed in 1997 depicted the seasonal populations of Aspen. In addition to the year-round residents of Aspen, there were occasional residents and overnight tourists, making Aspen's population 13,715 people that summer. During the winter season, Aspen's population was about 14,514 (Aspen Chamber of Commerce, 2006).

Rural Residential Water Users

The rural landscape of the valley has experienced varying degrees of fragmentation from urban sprawl. A 1994 study investigated the relationship of landscape (land cover) fragmentation to urban sprawl in the Roaring Fork/Colorado River corridor (central basin and lower basin) from 1985 to 1999 (Platt, 2004). The models demonstrated that the fragmentation of urban development was driven by desire for amenities. Platt explains this relationship by the fact that wealthy Aspen area people often seek large private houses on large plots of land that are adjacent to public lands and located away from the urban center. These single residence developments and ranchettes are often in former agricultural areas and off the municipal water utility service grid. While this study was for the central and lower basins, this type of trend has also occurred in areas along the Roaring Fork Valley from Basalt up to Aspen.

Hydroelectricity

Aspen has a long history of hydroelectric power usage. In fact, in 1885, Aspen became the first U.S. city west of the Mississippi River to light its streets and businesses with hydroelectric power. The hydroelectric power, which was generated by piping water from Castle Creek through a wooden flume to holding tanks on Aspen Mountain, was also used to power the mines near Aspen. This was an innovative first, according to a book entitled "Power in the Mountains: A History of the Aspen Municipal Electric Utility" (Anderson, 2004). The hydropower system fulfilled all of Aspen's electrical needs until 1958, when the city decided to dismantle the system and purchase their power from the grid (Urquhart, 2004). Today, 57 % of Aspen's electricity is provided from renewable sources like wind farms or hydroelectric plants. The majority of the renewable energy utilized by Aspen (35%) comes from hydropower generated from the operation of Ruedi Reservoir on the upper Fryingpan River. However, 5.4% of the city's electricity demand is generated by a small hydroelectric plant on Maroon Creek, a smaller tributary to the upper Roaring Fork River, using the water that remains in the creek that is not diverted for potable water supplies (Anderson, 2004). Additionally, Aspen is currently investigating the possibility of expanding its hydroelectric capabilities and once again utilizing the waterpower of Castle Creek for some of its electrical needs (Urquhart, 2004). In March of 2006, Aspen Skiing Company, operator of four ski mountains and two hotels in Colorado, purchased renewable energy certificates from wind farms to offset 100 percent of its electricity use. The purchase was the largest in the history of the U.S. ski industry.

Today, 57 % of Aspen's electricity is provided from renewable sources like wind farms or hydroelectric plants.

Recreational Water Use

For many mountain Colorado communities, winter and summer recreation drives tourism, which is the dominant source of income for residents. The Roaring Fork Valley, specifically Aspen, is no exception. Recreation in the valley can be subdivided by seasons. In the winter, the dominant recreational activity of the Roaring Fork Valley is skiing. There are four alpine ski areas in the area around Aspen. Several dominant summer recreational activities include rafting, fishing, and golfing. All of these activities require the use of surface water flows from the upper Roaring Fork River or its tributaries. Rafting and fishing physically utilize the surface water in the river channel, while skiing and golfing require the removal of surface water from the river for snowmaking and irrigation, respectively.

There are numerous recreational opportunities in which visitors and residents may participate on the upper Roaring Fork River, most notably fishing and river rafting. The upper Roaring Fork River extends from the headwaters near Independence Pass downstream approximately 30 miles to Basalt. Above Aspen, the river is characterized as straight, small, narrow, canopied with overhanging vegetation, and of steep gradient (a loss of over 80 feet per mile [15 meters per kilometer]) (BRW, 1999). From Aspen to Basalt, the river widens and becomes a more meandering body of water (though channelized in some areas). The gradient decreases from 80 to 60 feet per mile (15-11 meters per kilometer) (O'Keefe and Hoffmann, 2003). Instream recreational opportunities depend upon there being water in the river. The instream flow, deemed to be correct for the Roaring Fork River through the city of Aspen by the CWCB, is 32 cfs (0.9 m^3s^{-1}) (Enartech, 1994; Enartech, 1997). While water rights owned by the City of Aspen are typically senior to the instream flow rights, the city has made it a policy to, when possible, bypass sufficient water to maintain junior instream flow rights and maintain the ecological integrity of the river recreational opportunities (Enartech, 1994).

Fishing

Recreational fishing is of immense importance to the entire Roaring Fork Valley, as evidenced by the plethora of fishing outfitters in the area (BRW, 1999). The river has excellent fishing both above and below Aspen. However, the lower reaches provide better fish habitat with lower gradient, overhanging banks, deeper pools, and riffle areas (USDA Forest Service, 1981). The Roaring Fork is classified as Wild Trout Waters and Gold Metal Waters from Hallam Lake (in Aspen) downstream to upper Woody Creek Bridge (between Aspen and Basalt).

At the time off this report, the authors did not have user estimates for the upper Roaring Fork. However, five guides, who service three miles of the Fryingpan River one mile off the Roaring Fork near Basalt, took 1,200 clients on the river in 1996 and 1997 (BRW, 1999).

Rafting

Commercial rafters utilize the water of the upper Roaring Fork River (Aspen to Basalt) and the lower Roaring Fork (Basalt to Glenwood Springs).[28] The reaches of the stream above and directly below Aspen are narrow and are not suitable for rafting. However, kayakers use this upper section of river, as well as the lower reaches. Though rafting numbers in the lower Roaring Fork (below Basalt) are much greater than in the upper section, and usage in both section fluctuates with flows, recreational rafting in the upper Roaring Fork showed approximately a 20% increase per year in the late 1990's. In 1999, there were approximately 5,000 commercial rafting user days on the upper Roaring Fork. Drought in 2002 greatly affected river flow, preventing operation of commercial rafting, and resulting in zero commercial user days. However, in 2003, with flows still below average, the rafting numbers partially rebounded in the upper reaches of the river. Commercial outfitters reported a total of 2,000 user days in 2003, which resulted in an economic impact of $500,000 for the area (Colorado River Outfitters Association, 2003).

Skiing

The winter tourism industry in the valley is dominated by skiing. Aspen is a premier destination for both Colorado Front Range and out-of-state winter enthusiasts. Skiing and other snow related sports are dependent on sufficient snow at the right time. In particular, it is imperative and expected that the ski areas of Colorado have sufficient terrain open for use by vacationing skiers by the winter holidays each year. In order to open regularly at Thanksgiving or Christmas and lengthen the ski season, ski areas began to invest in and expand snowmaking capabilities (Best, 2001).[29] Snowmaking has become an integral part of ski area operation in the mountains of Colorado, including areas operated by the Aspen Skiing Company.

Snowmaking has become an integral part of ski area operation in the mountains of Colorado, including areas operated by the Aspen Skiing Company.

Aspen Mountain, Aspen Highlands, and Buttermilk Ski Area all use water that originated in either Maroon Creek or Castle Creek, two tributaries in the upper Roaring Fork Watershed. According to the 2003-2004 Aspen/Snowmass Sustainability Report, the three mountains used approximately 98 million gallons (370,970 m^3) of water on 430 acres (174 ha) of terrain for snowmaking purposes in the 2003-2004 season (Aspen Skiing Company, 2004).[30] Snowmass ski area, the northern most ski area owned by the Aspen Skiing Company, pumps water from Snowmass Creek into Brush Creek, where the resort then uses approximately 64 million gallons (242,266 m^3) of water on 160 acres (64.7 ha) of terrain for snowmaking purposes (Condon, 2006; O'Keefe and Hoffmann, 2003). A majority of the water diverted for snowmaking makes it to the aquifer or back to the river. Estimates of consumptive use for snowmaking are not generally available.

Golfing

The upper Roaring Fork Valley is home to a number of golf courses, including the Aspen Golf Club, the Snowmass Club, and the Maroon Creek Club. The Aspen Golf Club draws its water from Maroon Creek and Castle Creek. The Maroon Creek Club draws its water primarily from the Willow Ditch, out of the East Willow Creek drainage; however, during a dry year the club may use its rights in the Herrick Ditch, which does originate in Maroon Creek. At the time of this report, we were unable to determine the amount of water that is applied annually to golf courses in the valley, but in general, golf course irrigation can be very water intensive. However, the Aspen golf course holds 16 distinct water rights on Castle Creek totaling almost 10 acre feet, though rights held are not associated with usage. On average, a golf course in the United States will use 300,000 gallons of water per day during operation, but this value varies widely depending on region (Davies et al., 2004). Only approximately 50% of the water applied to greens and fairways will return to the river or alluvial aquifer via runoff and infiltration. This percentage is based on levels of return flows from lawn irrigation after evaporation and transpiration from Front Range communities (District Court Water Division NO. 1, 1987).

---

28. Commercial rafting trips on the upper Roaring Fork begin 5 miles (8.0 km)below Aspen at Woody Creek and end by Basalt. The trip covers 13 miles (20.9 km) of the river.

29. The drought of 1976-1977 in Colorado caused a 40 percent reduction in lift ticket sales, a 15 percent drop in employment, and a total of $78 million in losses. In response to the heavy economic losses, Colorado's ski areas began to heavily invest and install expensive snowmaking equipment to fight the impacts of future droughts (Colorado Water Resources Research Institute, 2002).

30. The water used by Aspen Highlands Ski Area, 18 million gallons (242,266 m^3) per year, is delivered via the city of Aspen's Maroon Creek Pipeline, which is part of the city's potable water supply (Enartech, 1994).

The Snowmass Club, located in the town of Snowmass, has recognized that there are alternative options to using potable water or river water for irrigation. The golf course has a number of water rights it employs to satisfy its water needs, including a right to water from Brush Creek. However, in 2001, a significant water-recycling program was introduced for the Domestic Water Treatment Plant in Snowmass. Under the plan, "grey water" from domestic use is processed at the water treatment plant, discharged into Brush Creek upstream of the golf course, and then removed by the course at the intake diversion (G. Van Moorsel 2006, pers. comm., 27 April). About 30,000 gallons per day are available for golf course irrigation from the water treatment facility (The Green Room, 2005).

Agricultural Water Uses

Agricultural activities in the valley require use of the Roaring Fork River and its tributaries for irrigation and watering of livestock. The majority of water usage occurs in the upper to middle Roaring Fork Basin between Aspen and Basalt along the mainstream of the Roaring Fork, as well as in the sub-watershed basin of Snowmass Creek (Clarke, 2006). Agricultural lands traditionally require a disproportionate amount of water to the overall percentage of land they occupy. For example, agricultural lands throughout the entire valley (70 miles [112.7 km] from Independence Pass to Glenwood Springs] comprise approximately 3% of land use, and rangeland comprises approximately 34% of land use. According to the 2005 Roaring Fork Watershed inventory, in 1995, irrigation was responsible for 93% of the Valley's total water use (O'Keefe and Hoffmann, 2003; O'Keefe and Hoffmann, 2005). However, it does not appear that the Watershed Inventory differentiated between types of irrigation (i.e. irrigation of a hayfield vs. irrigation of a golf course). Consequently, the percentage most likely overstates actual usage by the Valley's agricultural sector, though it does demonstrate that irrigation is the principle water user in the valley.

North Star is an important component of the Roaring Fork Watershed. The alluvial substrate near the river channel captures annual snowmelt through recharge, thus creating the wetland features of the area.

The Salvation Ditch

The dominant in-basin irrigation feature in the upper Roaring Fork region is the Salvation Ditch. Built in 1903, the ditch diverts water from the Roaring Fork River near Stillwater Road above Aspen and transports it twenty miles via an earthen ditch system to agricultural sections in the Woody Creek and McLain Flats area (G. Beach 2006, pers. comm., 31 March). The ditch is responsible for diverting about 10% of native river flows from the Roaring Fork above Aspen. The Salvation Ditch Company is a collection of shareholders, mainly farmers, ranchers, and homeowners that maintain and benefit from the ditch. Typically the ditch flows from mid-May to mid-October. The operation of the ditch may significantly impact the river in low flow years because the rights in the ditch are very senior, dating back to 1902, and pre-date instream flow rights (Urquhart, 2002; Colorado Judicial Branch, 2000). The direct flow rights adjudicated to the Salvation Ditch total 58 cfs (1.6 m^3s^{-1})(Colorado Judicial Branch, 2000).

Ecological Uses: The North Star Nature Preserve

There are a number of important ecological aspects of the entire length of the Roaring Fork River that could be discussed in great detail, ranging from bald eagle habitat to high-quality trout waters. However, the following section focuses on the 1.5 miles (2.4 km) of stream above Aspen known as the North Star Nature Preserve. This section of the upper Roaring Fork meanders slowly through a wide floodplain, before it returns to its fast moving, high mountain headwaters classification as it flows into Aspen. The North Star Nature Preserve is a topographically and ecologically unique 175 acre (70.8 ha) tract of open space land that is owned and managed by Pitkin County (Pitkin County, 2005).

Effect on River Flows

The topography of the preserve contrasts sharply with regional landforms. The preserve is a relatively flat, wide valley bottom surrounded by the steep mountain slopes of Richmond Ridge to the south and Smuggler Mountain to the north, a result of the glaciation of the Pleistocene Epoch (Pitkin County, 2005). The river meanders across the valley system and has created a landscape of old river channels and oxbow lakes. These form a unique and consistent riparian habitat for migratory and breeding waterfowl, wetland-dependent amphibians and birds, and small mammal species (Pitkin County, 2005).

North Star is an important component of the Roaring Fork Watershed. The alluvial substrate near the river channel captures annual snowmelt through recharge, thus creating the wetland features of the area. Additionally, the North Star Preserve is the principle ground water discharge area for the upper watershed. Water is transmitted from hill slopes and the regional system to the river and valley bottom aquifer (Hickey, 2000). Consequently, this 175-acre (70.8 ha) area is instrumental in providing base flow to the river during lower flow periods. It also moderates flows during periods of snowmelt and high runoff.

Ecological Uniqueness

The North Star area has remained relatively isolated and protected from the pattern of urbanization and land fragmentation that typifies locations down valley from Aspen, and in other mountain communities around the state (Hickey, 2000). Historically, the area was dominated by willow riparian vegetation communities with islands of cottonwoods and blue spruce (Pitkin County, 2005). However, from the late 1940's forward, the area was cleared of its natural vegetation and drained in some locations. The river was channelized so that the property could be used for cattle grazing. Due to the efforts of the Nature Conservancy and Pitkin County in the late 1970's, the land was designated as open space. This prevented housing development in the area (Pitkin County, 2005). Since the land has become open space, the plant communities of the preserve are slowly reverting to their natural conditions (Hickey, 2000). Hickey et al. (2000) indicate that there are 10 distinct vegetation communities that support high levels of biological diversity in terms of small mammals, birds, and large mammals.[31] This diversity is an indication of a healthy riparian habitat (Hickey, 2000). The documented presence of sensitive species at North Star, such as the Merriam's shrew, great blue heron, and other bird species that are declining elsewhere in Colorado, indicates that the preserve is a refuge for these species (Hickey, 2000).[32]

Pitkin County manages the area for low-impact recreation, to preserve native ecological communities that support a high level of biological diversity, and as an environmental education site (Hickey, 2000; Pitkin County, 2005). The 2005 North Star Preserve management plan states:

"The North Star Nature Preserve is a valuable resource to both Pitkin County and the city of Aspen for many reasons, including:

- as a sanctuary for wildlife
- as a public amenity for quiet recreation, including fishing, canoeing, and nature
- appreciation
- as a visual resource on a scenic highway entering Aspen
- as a vital area for clean air and water quality
- as a living classroom for environmental education
- as a deep underground aquifer, the North Star Nature Preserve sustains the health of the Roaring Fork River
- flood abatement in wet years and river recharge in dry years (Pitkin County, 2005)"

Though the list above is related to the North Star Preserve, many of the ecologically important characteristics can be attributed to the entire Roaring Fork River as well.

Trans-Mountain Diversions

Trans-mountain diversions are water right diversions that remove and transport water from watersheds on the Western Slope to the other side of the Continental Divide. Trans-mountain diversions can have a significant impact on river systems because, unlike in-basin diversions, which return some water back to the stream, trans-mountain diversions do not return any water to the basin of origin. In headwater river systems, like the upper Roaring Fork, trans-mountain diversions require close management because low river flows at certain times of the year make the river susceptible to impacts from further reductions in flows.

Trans-mountain diversions can have a significant impact on river systems because, unlike in-basin diversions, they do not return any water to the basin of origin.

In the trans-mountain diversions on the upper Roaring Fork, water is taken from the Roaring Fork and the Colorado River Watershed and added to the Arkansas River Watershed. There, it is primarily used for municipal water supplies for Front Range communities like Colorado Springs and Pueblo. Secondarily, the water is used for the irrigation of melons and other crops in the Arkansas Valley (Condon, 2005). According to a member of the Colorado Water Conservation District, 80% of the water that is diverted out of the Roaring Fork Watershed is for municipal and industrial uses, and the remaining 20% is utilized by agriculture (Condon, 2005).

There are two trans-mountain diversion tunnels that directly affect the upper Roaring Fork River: the Twin Lakes Tunnel and the Hunter Tunnel (Figure 1.2). The Twin Lakes Tunnel is the larger of the two systems. It includes about 12 miles

31. The physical size and density of trout populations in the North Star portion of the river is smaller than in other parts of the river. This is due to the sandy bottom of the channel and a lack of woody debris for protection from predators and heat (Pitkin County, 2005).

32. The North Star Nature Preserve Resource Management Plan states, "It is estimated that there are only 63 great blue heron colonies in the entire state of Colorado and the North Star colony is thought to be one of just a few occurring over 8,000 feet (2438 m) in elevation and is the only one occurring in blue spruce trees (most occur in cottonwoods). In other words, the North Star great blue heron colony is quite unique and ecologically significant." (Pitkin County, 2005).

(19.3 km) of tunnels, culverts, and ditches that collect water in Grizzly Reservoir before it is diverted over to the Arkansas River Basin (Clarke, 2006). The second, and smaller trans-mountain diversion in the upper Roaring Fork, is Hunter Tunnel which diverts flows from Hunter Creek.

Twin Lakes Tunnel

The Twin Lakes Tunnel, sometimes referred to as the Independence Trans-mountain Diversion Tunnel (ITDT), is operated by the Twin Lakes Canal Company and has conveyed water out of the Roaring Fork Valley since 1935 (Sloan, 2004). Today, Colorado Springs holds a 51% stake in the private water diversion firm. Under the Twin Lakes Canal Co. diversion scheme, water is diverted from the upper Roaring Fork River at Lost Man Lake through tunnels and canals (Clarke, 2006). The water is then discharged into Grizzly Reservoir on Lincoln Creek before it is diverted through the Twin Lakes Tunnel, under the Continental Divide. Eventually the water flows into Twin Lakes via the north fork of Lake Creek in the Arkansas River basin (BRW, 1999). The Twin Lakes Tunnel has the capacity to divert water at a rate of 625 cfs (17.7 m^3s^{-1}) under the continental divide (O'Keefe and Hoffmann; Sloan, 2004).

The Twin Lake Canal Company has the legal claim to divert 60,000 acre-feet (74,008,910 m^3)of water annually. However, the company never had the storage and availability to exercise withdrawal of the full amount (Hartman, 2004). The Twin Lakes Tunnel typically delivers around 40,000 acre-feet (49,339,273 m^3) annually to the Arkansas River Basin and Front Range communities. The withdrawals from the main stem of the upper Roaring Fork River by the Twin Lakes Canal Company result in approximately a 40% decrease of native flows that would reach Aspen if the Twin Lakes Tunnel were not in operation (Hartman, 2004).[33]

> **The withdrawals from the upper Roaring Fork River by the Twin Lakes Canal Company result in approximately a 40% decrease of native flows.**

The Hunter Tunnel

Hunter Creek, a tributary of the upper Roaring Fork, is located immediately east of Aspen and is partially within the Hunter-Fryingpan Wilderness. The Creek's confluence with the Roaring Fork is within the city limits on the north side of the town. As part of the United States Bureau of Reclamation's Fryingpan-Arkansas Project, water is diverted from the upper reaches of Hunter Creek, collected with other diversions from the upper Fryingpan headwaters, and conveyed under the continental divide through the Boustead Tunnel to Turquoise Lake west of Leadville.[34]

In-Basin Users

The Shoshone and Cameo Calls

There are two major water rights outside of the Roaring Fork Watershed that affect the streamflow and users of the Roaring Fork River, especially of the upper Roaring Fork: (1) a group of Grand Junction water rights collectively known as the Cameo Call, and (2) the Shoshone Hydroelectric Plant (Shoshone Hydro) in Glenwood Canyon, eight miles east of Glenwood Springs (Sloan, 2004). These entities both possess very senior water rights. The earliest call rights of Shoshone date back to 1905 and the earliest call rights of the Cameo date back to 1912.

When either entity makes a "call" on the river, junior water rights holders are required keep water instream until it reaches the Colorado River (in the case of the Shoshone Call) or the Grand Valley Canal near Grand Junction (in the case of the Cameo Call). The result is that upstream diversions, including the more junior trans-mountain diversions to Front Range municipalities, must cease and upstream reservoirs may need to release additional water into the river to satisfy the senior water rights of Cameo and Shoshone calls (Sloan, 2004). Presently, the Cameo Call operates only during the irrigation season in the Grand Valley, which can range from April to October in dry years. The call's length depends on how dry the season is and how much water is diverted by junior users upstream. In drier years, the Division of Water Resources administers the call earlier in the season. Regardless of dryness, though, the Cameo Call comes every year simply because the river is over-appropriated (Sloan, 2004).

In-basin junior rights holders are rarely prevented from taking full or partial amounts of their decreed water rights from the Roaring Fork River. However, in very dry years, it is possible that, at times, diversions from the Roaring Fork Valley may be curtailed completely to certain users. This was the case in August 2003 when the Cameo Call forced the Twin Lake Canal Company to stop diverting water through the Twin Lakes Tunnel. While the call negatively impacted Front Range

33. Another 10% of native flows leave the Roaring Fork River above Aspen at the Salvation Ditch, which waters hayfields and ranches down the valley. If these withdrawals are combined with those of the Twin Lakes Canal Company, approximately 50% of the native flows of the Roaring Fork River never reach Aspen (Hartman, 2004).

34. The Fryingpan-Arkansas Project is a multipurpose trans-mountain, trans-basin water diversion and delivery project that uses two tunnels (the Boustead Tunnel and the Busk-Ivanhoe Tunnel) to deliver an average annual diversion of 69,200 acre feet (85,356,943 m^3) of water from the Fryingpan River and other tributaries of the Roaring Fork River, to the Arkansas River basin on the eastern slope (http://www.usbr.gov/dataweb/html/fryark.html).

municipal users and Arkansas Valley farmers, the result of the call on Roaring Fork Valley users was positive. Water was allowed to stay in the river, resulting in improved recreational opportunities on the river, such as fishing and rafting, and improved ecological conditions (Condon, 2003).

The Shoshone Hydro Plant is located on the Colorado River, eight miles upstream of the confluence of the Colorado River and Roaring Fork. Shoshone Hydro diverts water from the Colorado River as it flows through Glenwood Canyon into its turbines in order to generate electricity. After the water is passed through the turbines, it is released back into the Colorado River several miles from the point of diversion. In order for the plant to operate effectively, there needs to be sufficient flow in the River for Shoshone Hydro to divert. Consequently, throughout most of the year (except in spring run-off months when water in the Upper Colorado river system is in excess), Shoshone Hydro will make a call on the river (Sloan, 2004). The Shoshone Call prevents or moderates major trans-basin diversion from occurring upstream of the plant. Some of the upstream Colorado River basin users that are negatively impacted from the call include Denver's Roberts Tunnel, the Moffat Tunnel, and the Colorado Big Thompson Project.

So, how vulnerable is the upper Roaring Fork to global warming?

The Shoshone diversion can leave several miles of the river below the plant dry as many as twelve weeks out of the year, however the water is eventually returned to the river several miles downstream. Additionally, because 100% of the water used for electric generation is returned to the river, the net effect of the operation of the plant and the Shoshone Call can be beneficial for both the Colorado River and users of the Roaring Fork. For Colorado River users, the increased flows, as a result of the Shoshone Call, help provide environmental and recreational flows on the Colorado River both above and below the Shoshone plant. In particular, the Shoshone Call increases instream flows for the 15 mile reach (24.1 km) of the Colorado River below Glenwood Springs that is part of the State of Colorado Endangered Fish Recovery Program (S. Clarke 2006, pers. comm., 15 June). Furthermore, the Shoshone Call increases flows in the main stem of the Colorado as the water makes its way to the farmers of the Grand Valley Canal (S Clarke 2006, pers. comm., 15 June).

The operation of the Shoshone Hydro plant and the associated Shoshone Call impacts Roaring Fork River users in several ways. Because the Shoshone Call results in increased flows through Glenwood Springs and down to Grand Junction, the call may delay the Cameo Call and demand for water to protect the Colorado River Endangered Fish Recovery Program. Otherwise, without the Shoshone Call in place, water from the Roaring Fork River would be required to augment flows to meet the Colorado River demands leaving more water instream. When the Roaring Fork River flows are not required to be released downstream to the Colorado River for fish habitat protection or use by Grand Valley farmers, they can be diverted elsewhere. Thus, the Shoshone Call mainly benefits Roaring Fork trans-mountain diversions. The resulting lower flows in the upper Roaring Fork River can negatively impact Roaring Fork instream users, such as rafters, and negatively affect fish and riparian habitat.

6.3.2 Potential Impacts on Uses from Changes in Runoff

Results from the runoff modeling discussed in the previous section indicate that several changes to the annual hydrograph can be expected:

- increased flow in mid-winter (January-March),
- a shift in peak flow from June to May, and
- less early and mid-summer snow melt (due to the mid-winter melt event) resulting in low June flows.

The runoff analysis also indicates that monsoon moisture may increase July-August flows by the year 2100; however, caution should be used when evaluating the validity of this. Climate models predict changes in temperature with relative confidence, but can struggle with precipitation predictions. If monsoon events do not occur in July, the result will be an overall decrease in flows in the summer months (B. Lazar 2005, pers. comm., 26 April). Therefore, low June flows, as well as low overall summer flows, are possibilities that must be considered by users of the Roaring Fork River.

Potential Impacts on Municipal and Rural Water Users
Overall, affects from changes in Roaring Fork runoff on municipal and rural water users will most likely be limited. The yearly volume of water flowing through the Roaring Fork system will remain relatively unchanged, but changes in the hydrograph may have some impacts to municipal users. For example, as noted earlier, there is a possibility that the frequency of water shortages may increase with urban growth in the valley without considering the effect of climate change, especially during base flow periods (winter months). Therefore, higher flows in the winter months as a result of predicted climate change would help meet winter demand and alleviate pressure on the alluvial aquifer that would otherwise be pumped. Additionally, if the city did not need the increased winter flows to meet potable demand (including

snowmaking), the city might be able to increase its electricity generation in winter months through the hydroelectric plant on Maroon Creek (Enartech, 1994).

Potential adverse effects from decreases in June flows or summer flows (if the July monsoon does not occur) may be mitigated through using more of the city's storage, or by curtailing the municipal outdoor water usage in the summer. The city could also increase pumping of the alluvial aquifer, but as noted earlier, this would further lower flows through the city of Aspen as well as instream flow for a significant portion of the year (Enartech, 1997).

Potential Impacts on Recreational Users

Weather and climate have a significant influence on the tourism and recreation sector of the Roaring Fork Valley, especially in terms of snow cover for skiers and river flows for rafters and fisherman.

Potential Impacts on Commercial Rafting

Rafting companies could be significantly impacted by a shift in the hydrograph. The results from the modeling show that peak runoff will arrive in May rather than June and that June will be characterized by reduced flows in 2030, when compared to 2001. June flows may become more consistent with flows found currently in mid-July. Now, the majority of rafting in Colorado waters occurs from mid-May to August. On the upper Roaring Fork, the season typically extends from Memorial Day weekend through July. Significant warming in June results in a peak runoff event. The current hydrograph is fortunately congruent with vacation and tourism seasons. Therefore, even if the year 2100 climatic conditions and flow regimes of May are identical to those of June 2001, significantly reduced flows in June 2100 could reduce the rafting client base of the upper Roaring Fork River. Though the premier rafting season will be in May at that time, tourists will still be constrained by traditional vacation periods. Therefore, potential rafting clients arriving in June may be forced to find other recreational activities or to travel downstream to the lower Roaring Fork or the Colorado River. Those sections have larger drainage basins and flows are kept constant by the Shoshone power plant in Glenwood Canyon.

Modeling results also indicate that in 2100, it is possible that the Roaring Fork River could see higher flows in July because of summer monsoons. Monsoonal events could result in increased user days in the month of July as compared to 2001 and 2030, and may dampen any negative economic impact that rafting companies experience as a result of reduced demand in June because of low flows. However, as noted, the monsoonal event is uncertain. It is just as likely that, like June, flows will be lower in summer through fall as well. Rafting is highly sensitive to flow regime, as was seen in 2002 during the drought. Overall, lower flows in the summer may significantly impact recreational rafters and outfitters.

Potential Impacts on Recreational Fishing

Similar to rafters, the projected, one-month-earlier shift of the hydrograph may force fisherman to modify their schedules to accommodate changing river conditions. Fishing of high mountain rivers is prevented in times of peak runoff by the turbulence of the streams and lack of water clarity. If peak runoff were to occur earlier, the anglers could fish the main steam of the Roaring Fork the entire month of June, whereas before, flows were too high to allow fly-fishing. However, they would no longer be able to fish in a portion of May. Also, lower flows in June and July and increased water temperatures could potentially have adverse effects on fish populations. This is discussed in detail in the Ecological Impacts section below.

> Weather and climate have a significant influence on the tourism and recreation sector of the Roaring Fork Valley.

More likely, low flows would cause a shift in people's perceptions. For example, the biggest obstacle faced by fishing guides in Colorado during the drought of 2002 was convincing fisherman that the fishing was still very good with lower flows (Colorado Water Resources Research Institute, 2002). During the summer of 2002, gear sales were down 30%, guide trip sales were down 20%, and many fishermen who were repeat customers to local Colorado outfitters traveled to other western states where water levels were higher (Colorado Water Resources Research Institute, 2002). The biggest expense for fishing outfitters in the Roaring Fork Valley, as a result of the predicted climate changes, may be an increase in their marketing and informational campaign budgets.

Potential Impacts on Skiing

Aspen-area ski resorts use the waters from Maroon, Castle, and Snowmass Creeks for snowmaking. Snowmaking occurs as early as October, but mostly in November and early December. Runoff model results indicate that flows during this time period will remain essentially unchanged. Therefore, the changes in the flow regime of the Roaring Fork River and its tributaries will mostly likely not impact the four Aspen Skiing Company mountains. Increased air temperatures and a shorter season resulting from loss of spring snowpack and shorter winters, as well as by people's perceptions of snowpack and ski quality, will more likely impact the ski areas. And though impacts may not be as significant as those from the 1976-1977 drought (since resorts now have better snowmaking capabilities), increases in temperatures may delay the ability of resorts to use snowmaking equipment.

Potential Impacts on Golf Courses

Golf courses are in the business of growing grass. Golf courses require large amounts of water to sufficiently irrigate greens and fairways. However, a shift in the hydrograph may not significantly impair a course's ability to operate. Warmer temperatures, which cause the earlier peak flow events, would allow a course to open earlier and perhaps use water when it was most available. Lower flows in June or July could be problematic for a golf course. However, golf courses do have a suite of adaptation options available to them, though at a cost, if less water is available in June and July for irrigation. These include the use of wetting agents, a move to a less water intensive and more drought-resistant turf, the addition of more areas of natural vegetation to decrease irrigated acreage, employment of better irrigation techniques, and investing in the use of reclaimed water (G. Van Moorsel 2006, pers. comm., 27 April).

Potential Impacts on Agricultural Water Users

Agriculture in the Roaring Fork Valley primarily consists of livestock production and the growing of hay. A shift in the hydrograph could have a significant impact on ranchers in the valley. First, if snowmelt runoff is reduced in the early summer months because of earlier melting in January-March, soils and vegetation may become drier. Thus, increased initial irrigation on hayfields may be required, which could lead to increased pressure on water resources. However, some techniques are available to help, such as the lining of irrigation ditches to prevent conveyance losses.

A shift in the hydrograph could have a significant impact on ranchers in the valley.

Additionally, if the predicted monsoonal events of July do not occur, irrigation demands will be similar, if not higher, to those of 2001, due to warmer temperatures and higher levels of evaporation. However, river flows will be lower, which will result in calls on the river, forcing those with junior rights to leave water in the river. However, higher temperatures could be offset by increased levels of atmospheric concentrations of carbon dioxide, which reduces water demand by plants. Livestock production may be more susceptible to the stresses of increased heat rather than to months of low flows (Adams, et al., 1999).

An additional issue that may arise with lower flows in the summer is that the diversion structures, if not modified, may not be able to divert sufficient water to meet demands. The structures, such as Salvation Ditch, were constructed with the expectation of certain flow levels. If those levels are not reached, diversion may not be possible.

Though precipitation in July has obvious benefits to the agricultural sector and golf sector in the valley, the potential monsoonal events in July may result in flooding in certain areas and increased erosion of agricultural lands or areas that have been disturbed by livestock.

Potential Impacts to the Ecological System

The potential impact of the predicted shift in the hydrograph, and associated changes in water resources on the river system, are well studied in the Roaring Fork watershed. However, given the complexity of the system, it is uncertain if the net result would be positive or negative.

The flow regime of a stream is one of the most important factors influencing aquatic communities. Adequate, year-round, instream flows are needed to maintain aquatic habitats. The flow of a river or stream has both direct and indirect effects on the aquatic community. Flow is highly correlated with essential habitat factors such as stream depth, velocity, dissolved oxygen, concentrations, thermal changes, renewal of aquatic resources, and food supplies (Ptacek et al., 2003). The aquatic and riparian communities of the Roaring Fork are a product of the current flow regime. If the regime is changed, the aquatic and riparian communities will be altered as well.

A shift in the timing of runoff in the watershed, because of May's higher temperatures and the arrival of peak flows earlier in the year, could have significant impacts on the success of trout spawning and trout survival (Ptacek et al., 2003). Additionally, if flows are extremely low in June, as a result of the earlier spring runoff, and water temperatures are higher, stream insect development may be affected. On the other hand, the increased flows in the winter months could have a positive impact on the river communities. In the winter months, an indirect effect of low flows, in conjunction with cold temperatures, is the formation of anchor ice.[35] Midwinter melting events, like those predicted in the model, would increase winter flows, reduce anchor ice, thus alleviating disturbance of the riverbed.

Changes in water levels can affect wetlands, riparian

35. Anchor ice forms on the bottoms of rivers and streams in shallow, turbulent sections (O'Keefe and Hoffmann, 2003). Because anchor ice adheres to the bottom of streams and rivers, and then breaks away as the temperature warms, it often scours the substrate surface, disturbing plant matter, macro-invertebrates, and the spawning beds of trout. This phenomenon can seriously affect the river bottom and its inhabitants, though periodic anchor ice scouring events can improve habitat by removing excess plant growth (O'Keefe Hoffmann, 2003). The formation of anchor ice occurs annually in the Roaring Fork Valley, but the frequency of events and overall impact are unknown.

vegetation, and habitat, as well as aquatic habitat. Loss of vegetation in the riparian zone that provides shade to the river (stream cover) can result from low flows in streams and rivers (U.S. Bureau of Reclamation, 1983). The loss of stream cover has a compounding effect because stream cover helps regulate water temperature and provides cover for aquatic species. A healthy, functioning riparian area, such as the one currently found in the upper Roaring Fork, provides a high-density of macro-invertebrates and thus can support healthy populations of trout that feed on this food supply (Ptacek et al., 2003). Consequently, a low stream with a loss of stream cover may be too warm, and will lack habitat and sufficient food supply for a healthy fish population as well as for riparian animals feeding on aquatic communities.

Lastly, July monsoonal events, if they occur, would have a positive affect on the Roaring Fork system through increased summer flows that would help reduce water temperature and improve water quality. However, heavy rain events could simultaneously have adverse effects. Cloudbursts can generate intense flows in the river channels and creeks that can cause bank instability, reduction in macro-invertebrate populations due to increased sedimentation from erosion, and channel migration, which in turn affects habitat (Pitkin County, 2005). This is of particular relevance for the North Star Nature Preserve with its unique topography. If North Star were to lose the meandering nature of the river channel, much of the unique riparian habitat would be lost as well.

Potential Impacts on Users Outside the Roaring Fork Watershed

Depending on the type of use, out-of-basin users may be impacted in varying degrees by a shift in the hydrograph. Recall that the trans-mountain diverters of Roaring Fork River water are Front Range communities, such as Colorado Springs and Pueblo. A shift in the hydrograph from June to May will most likely not have a great impact on these municipal entities. With large storage capacity, the Twin Lakes Canal Company could divert larger amounts of water earlier in the year (May instead of June) to take advantage of peak runoff. The reduced flows in June may result in the inability of Front Range communities to use Roaring Fork River water not already removed from the basin. Cities may respond to reduced summer diversions by expanding storage capacity to capture more water earlier in the season, buying additional rights from agricultural or other interests, or implementing additional conservation techniques.

Perhaps more at-risk trans-mountain users (though this is dependent on seniority of water rights on a case-by-case basis) are the farmers of the Arkansas River Valley. Increased temperatures, in conjunction with low flows, may threaten their ability to properly irrigate melons and other crops. However, the agriculture sector can adapt by shifting planting and harvesting dates, changing crop varieties used in particular areas, or by using more efficient irrigation techniques.

Changing climatic conditions will impact Grand Valley Canal farmers near Grand Junction. This, in turn, could affect users of the Roaring Fork waters in the Front Range and Arkansas River Valley. The farmers may find that reduced June (and perhaps summer) flows are not sufficient to meet their irrigation needs and may place a call on the river that would prevent trans-mountain diversions and other usage by more junior water rights holders. If the Cameo Call were initiated, it would have an interesting effect on all Roaring Fork River users. Given the size of diversions, farmers and municipalities of the Roaring Fork Valley may not have to curtail their use. However, the call would force more water to stay in the river. The low flows of June and perhaps the rest of the summer may be augmented by needs downstream in the Grand Valley. Issues of low flows, in regards to rafters, fisherman, municipal water users, in-basin agricultural interests, and ecological conditions that were discussed above, may be lessened or, in some cases, even disappear if a senior call were initiated.

Changes in water levels can affect wetlands, riparian vegetation, and aquatic habitat; lower flows in June and July and increased water temperatures could potentially have adverse effects on fish populations.

6.4 UPPER ROARING FORK STAKEHOLDER RESPONSES

We interviewed stakeholders that represented key users of the upper Roaring Fork. This was a "rapid assessment" in which a single stakeholder was a representative of that type of water user. We asked questions about:

1. Current sensitivities and flexibilities in regards to streamflow variability
2. Concerns about external forces and institutional change
3. Concerns about climate change

Thus we examined the chief sources of future uncertainty: those emanating from social, institutional, and economic factors; and those emanating from the natural environment.

Our stakeholder assessment was limited to ten in-depth interviews. It also included comments on a draft of the stakeholder assessment by reviewers who understood water issues in the basin and region, and who were, in a sense, stakeholders themselves.[36] By selecting stakeholders that represented a variety of interests in the basin, from municipal supply to recreation, we believe we captured the most significant stakeholder dimensions of water in the upper Roaring Fork. As described in the previous section, some stakeholders actually take (appropriate) water from the streams and apply it to some beneficial use such as irrigating pastures or golf greens, providing water to municipal and industrial users, etc. Other stakeholders have an interest in instream water, including commercial river rafting and fishing companies. These stakeholders have no water rights and must use the river as they find it (modified by climate variation and by other users). Another type of instream stakeholder has an interest in the environmental and ecological values of water in the streams. Policy or regulatory instruments may back that interest, or it may be expressed through advocacy, education, and other forms of social action.

Lacking storage, water appropriators must concentrate their use during the months of significant runoff.

Stakeholder interviews allowed us to obtain the facts, opinions, and perceptions grounded in the experience of actual water users. The interviews also uncovered vulnerabilities and adaptabilities that were not discernable in the documented sources used in the previous section.

6.4.1 Background

All users are affected by the upper Roaring Fork's normal hydrograph, which is typical of many Rocky Mountain settings. It exhibits a sharp peak during "the runoff" (maximum snowmelt and discharge, typically in June), and relatively low late summer, fall, and winter flows. Most of the users we spoke with have adapted to this annual flow variability, and can make at least some use of low flows. For example, an irrigation ditch manager can run at least small flows through the system into October, when ranchers may spread water to recharge their soil moisture in preparation for the next growing season. Others simply find the river unusable in certain flows. Fishing and whitewater raft guides in particular are subject to constraints imposed by flows. Advocates for ecological values tend to prefer the unperturbed hydrograph for its capacity to maintain a suite of natural structures and processes.

All users are also affected by institutional trends inside and outside the basin, including uncertain future actions of individuals and agencies that will affect water availability in the basin. Indeed, most stakeholders, and some of the reviewers, expressed serious concerns about population growth, water demand, re-allocations of water, and other changes driven by political and economic forces beyond their control. Stakeholders' response to this uncertainty is to support and protect the current water rights system, and to assure that their own rights are secured, though legal and physical protections.

6.4.2 Current Sensitivities and Flexibilities

The main sources of flexibility in water supply are storage or access to multiple sources. Some upper Roaring Fork appropriators have the ability to store some of the water they take within the basin, and use it at a rate that meets their needs. Some users in the basin are part of larger water management systems that store water outside of the Roaring Fork, and thus have additional flexibilities that help them adjust to runoff variations and to changing demands in the upper Roaring Fork proper.

But, overall, storage is very limited in the upper Roaring Fork. Most users are constrained to apply the water when it is in the streams, and thus available to be diverted into ditches and conveyed immediately to their point of use. Lacking storage, water appropriators must concentrate their use during the months of significant runoff.

Some upper Roaring Fork stakeholders count on multiple sources of supply as a hedge against insufficient flows, or, barring that, the simple reliability of a high-elevation snowpack/ runoff hydrologic system. The municipal supply system uses water from two tributaries, Castle and Maroon Creeks, and three wells arrayed around the valley floor. The wells experience significant annual variation in water level, peaking later in the summer after the runoff peak. The switch from surface to groundwater leads to availability of water through the high use period. The municipal system also reduces its risk by using water rights in local irrigation ditches for landscape, park, and even golf course irrigation with raw water. This is unlike many municipal systems in the West, which must irrigate with treated supply—the same supply that goes to taps.

36. Ten stakeholder interviews were conducted by the Aspen Global Change Institute in March and April of 2006. Transcripts of these interviews are archived by AGCI.

A local golf course manager, whose system also provides landscape irrigation for nearby properties and public areas owned by the city, relies on two ditches from different tributaries with slightly different flow characteristics. One may run dry by summer, whereas the other typically conveys water throughout the summer. In most years, the first ditch provides sufficient water, so in a sense the second-ditch water rights are a hedge or backup.

A user with only one source, like a rancher, must apply the water when it is available, by irrigating pastures in the spring and early summer and counting on summer rains to keep the grass going through the rest of the grazing season, into early October. A major ditch company may have no significant in-basin storage either, but relies on its senior rights, and the natural tendency of alpine basins to discharge water year-round, to keep water in the ditch for an extended season (May though October).

River recreation companies, as a form of instream stakeholder, of course have no control over streamflows, and no "storage" *per se*. They are vulnerable to natural and human-perturbed flow changes. Their flexibilities come in the form of operational adjustments. Clients may be placed on different stretches as flows rise and fall in the spring and summer, and may be taken outside the basin (to the Colorado and the Arkansas) when the Roaring Fork does not provide adequate recreational flows. Sometimes technological innovation can help. For instance, improvements and diversification in floating equipment (e.g., rafts vs. "whitewater duckies," which are inflatable kayaks that can navigate lower flows) allow raft guides to put clients on different water levels.

On an average year for the Roaring Fork, there are six weeks when the instream flows are not satisfied.

Ultimately, though, as the fishing outfitter recognized, there are limits to shifting method, time and point of use:

> *If you've got fishermen who want to fish or people who want to come to the valley and the water conditions are not ideal, that certainly is costing us business. Or, if we so choose when the water is very warm that we don't fish on a given day or time of the year, that's also a concern as far as cost goes. It costs us money if we make those decisions not to go out and fish.*

Environmental interests have a stake in the "natural" hydrograph (i.e., working to preserve natural flows, both high and low), or in modifications of the human perturbed hydrograph to accomplish instream flow goals, like maintenance of aquatic habitat. A major appropriator, like the municipal system, must also assess its impact on regulated instream flows, a problem exacerbated in dry years.

> *On an average year for the Roaring Fork, there are six weeks when the instream flows are not satisfied. In a dry year, I think it goes up to twelve weeks. The drier it is, the longer that window is. And there were only a couple years in the last 30 years where there weren't any issues – no shortages for instream flow at all.*

In the upper Roaring Fork case, the timing is such that the municipal system is usually on wells during the critical period, and can take less surface water.

Some stakeholders mentioned recent dry years that affected them or their industry. During summer 2002, a drought year, diversions virtually dried up the Roaring Fork in the vicinity of Aspen. Anglers, the city, and others were affected and have since developed agreements to try to prevent this in the future. In this case, mobility helped. Whitewater rafters and fishing outfitters can shift operations, especially downstream where larger flows are typical. Still, our whitewater rafting stakeholder pointed out that hauling clients elsewhere is not ideal. Clients don't like to travel far to float or fish, and it also costs the business time and money.

> *[Clients are] much happier driving for ten minutes and putting on the water right down here than driving for an hour and a half to put on down in Glenwood Springs. My busiest years are when we have a big season on the upper Fork here. People like to go rafting. And they want to go rafting right here. They're not paying for a bus ride.*

Finally, a significant source of flexibility in the system today is that some users are not actually diverting their allotted volumes. Our interviews included users who have sufficient rights to significantly reduce flows even further if they fully appropriate those rights.

Indeed, several stakeholders mentioned water rights that aren't fully used: ranging from the owner of a small property on the ditch used by the golf course (thus leaving more in the ditch and providing some buffer for the golf course), to a major ditch company that extracts less than its total allocation because of limits in demand or capacity, as well as formal and informal agreements to take less water. This, of course, is also a significant source of future uncertainty. Water rights holders cited several reasons for protecting their rights, which they expect to fully use in the future, resulting in reduced flows and the buffer capacity of water currently available in the system

6.4.3 Concerns about External Forces and Institutional Change

Worries about further diversions, population growth placing more demands on existing supplies, water "raids," and changes in timing of diversions (or of releases, e.g., on the Frying Pan), were expressed by almost all water interests in the basin. We believe these worries are the largest source of future uncertainty and concern among users. Although we have no scientific way of demonstrating this, our sense from the interviews is that these concerns worry upper Roaring Fork River stakeholders much more than does climate change.

Several stakeholders raised concerns about growth in the basin and elsewhere. A common refrain was something along the lines of "explosive population growth." In-basin growth can increase not only demand for water (though the local municipal system reported that it has enough water supply for expected "build out"), but can also affect water quality as more pollutants wash into the streams from lawns, golf courses, roads, etc. A rancher reported that people who buy nearby land might not understand western water law, and think they can simply find water for projects like trout ponds.

> *I've had neighbors who would like to have my water, and I've managed to convince them that we're not parting with it. There are people who will buy a piece of dry hillside and say, "we'd like to have a pond here – where's the water?"*

Worries about further diversions, population growth, water "raids," and changes in timing of diversions were expressed by almost all water interests in the basin.

A more common concern among our stakeholders was population growth in Colorado and the Colorado River basin, which is seen as a threat to local water supplies in the future.

One of the outside reviewers agreed that upper Roaring Fork water interests should be concerned about large-scale changes in allocations, including further transfers to the Arkansas basin and re-allocations within the larger Colorado basin. This reviewer believes that water users in the Lower Colorado Basin could eventually win re-allocations that would result in changes in tributary flows. The review concluded, wryly, that: "The debate within [the] Colorado will be interesting, if the water goes to Las Vegas or Phoenix, at least we can fish or raft in it as it goes by."

A concern voiced by some stakeholders (the municipalilty, ditch companies, and ranchers) was the need for vigilance concerning water rights and obligations. The municipal supplier made the point that the complexity of the system, with its dozens of diversions, head gates high in the mountains and streamflow gages at various levels, means that it is difficult for any one stakeholder to assure that operations are all being attended to, that rights are being protected, and that correct amounts are being diverted. The system on paper, and even the process of daily decision-making, may or may not yield flows as decreed by water law and contracts. The major ditch company had the same concerns, and found it was "policing" other users so as to protect its own water rights. One interviewer quoted an old adage that probably reflects concerns of many: "I would rather be upstream with a shovel, than downstream with a decree." In this vein, the ditch company and other rights-holders plan to use their full decreed flows. In many cases they do not right now, but fear of losing their rights encourages them to make plans to physically use all of their rights in the future.

Worries over water rights may not be illogical. At least two of the stakeholders with formal water rights expressed concern over the state's new "ten year abandonment list." The Colorado Division of Water Resources has developed, in consultation with the State Engineer, an abandonment list that contains those water rights that the Division Engineer has determined to be abandoned in whole or in part. The stakeholders felt there would be increased enforcement of the list, requiring more costly record-keeping and, more importantly, the need to use their allotted water rights so as not to lose any rights the next time the list is updated in 2010.

Several stakeholders noted that the Twin Lakes Canal and Reservoir Company, a major trans-mountain diversion near the headwaters of the Roaring Fork River, is not taking its full allotment for several reasons: limited need, inadequate capacity, and commitments to instream needs on the Western Slope. Yet the company has carefully protected its decreed allotment to ensure that it can take its full share in the future.

The two main instream recreational interests have different concerns about calls on water outside the Roaring Fork Watershed. The whitewater outfitter finds that outside demands, like those for endangered fish habitat on the Colorado River below the Roaring Fork, and calls for water by senior rights holders in the Grand Valley, can result in higher, mid-summer flows on the Roaring Fork (and the Frying Pan), allowing for a longer river running season. The fishing guide indicates that calls on the river meant for endangered fish and downstream senior rights, make their business more difficult. High water cuts into the time they can fish and serve clients.

On the other hand, whitewater guides use peak flow, and worry that other users inside and outside the Roaring Fork Watershed will argue that they should be able to divert more of the peak flow, while protecting the minimum flows. Ecological interests, who understand that peak flows maintain stream channel and riparian habitat, worry that further appropriations will attempt to skim off the larger peaks.

6.4.4 Concerns about Climate Change

"The debate within [the] Colorado will be interesting, if the water goes to Las Vegas or Phoenix, at least we can fish or raft in it as it goes by."

In our interviews we stressed rather simple notions of future climate change, based on the scenarios run by Stratus Consulting. In short, we urged stakeholders to consider a hydrograph with an earlier peak, and associated notions that low flow periods might yield even less flow. We suggested, from the scenarios, that total annual volume of flow might not change.

Stakeholders focused on the retrograded peak flow. Those without storage must determine how to use the peak flow when it comes. The rancher might worry that water would be available earlier but not when fields are ready to be irrigated. The municipal supplier might be concerned that an earlier peak means lower flow during the dry months, and raised the probability of drought years and poor years coming in succession.

The ski area manager was concerned about climate warming. If the main result of climate warming is a shorter ski season, and a later arrival of low temperatures for snowmaking, then the problem is not the amount of water needed to make snow, but the need to use the same amount of water later, and during a shorter period of time. This raises concerns about labor, operational and cost issues, and storage. A reviewer pointed out that making snow over a shorter period of time means using more water per unit of time, typically in a period when flows are at their lowest. The snowmaker must increase storage to provide that rate of water use, or else stream depletions will increase even more during the concentrated snowmaking period.

An earlier peak and lower flows may dramatically curtail whitewater recreation. On the other hand, an earlier peak would benefit the fly fishing season, because the peak flows would be over by the time most of the tourists showed up to go fishing. The guide told us: "If we saw that peak runoff happening in mid-May rather than in mid-June, then it would be more fishable by the time summer tourism happens."

A reviewer raised the concern that earlier runoff and warmer temperatures also mean more rain events, and rain-on-snow events, that could intensify the runoff and cause flooding. This could also thwart storage schemes, based on the current hydrograph.

Another reviewer pointed out that recreation is not just floating or fishing, but that water in lakes and in streams is a critical aesthetic resource in a tourism-based economy.

> *Where there is a river or creek or lake, there are people. Backpackers rely on rivers and creeks for their water. Photographers more often than not have themes that revolve around lakes, rivers and streams. Nothing like a flowing river to rejuvenate the human soul and provide an environment for thought.*

Several stakeholders mentioned the 2002 drought experience. The river was so diminished that it ceased to be the aesthetic resource on which the region relies. They worried about climate change undermining this foundation.

6.4.5 Other Concerns

Although our focus was on water quantity, several stakeholders identified quality as a significant concern, and recognized that the two were closely related.

- Fishing outfitters worried about quality. They were also concerned that stream temperatures would increase during periods of low flow, which would reduce both insect and fish health.
- The municipal supplier must deal with variations in quality that must be treated, and that alters the quality delivered to the user.
- Environmental stakeholders were concerned about sufficient flows for dilution of heavy metals and other pollutants.

6.4.6 Summary of Key Points made by the Ten Interviewees

PHYSICAL APPROPRIATORS: A municipal utility director, an irrigation ditch manager, a rancher, a golf club manager, and a ski area manager

Current and future concerns voiced by the stakeholders:

- Unchecked population growth resulting in increased diversions to the front range, increased calls on the river by the Lower Basin states, and the addition of more junior water rights locally and downstream
- Earlier peak run-off when hay fields, crops, and turf grass are not ready to start growing
- Earlier peak run-off means that ski areas will melt earlier
- Weather variability – if the temperatures get warmer earlier, what happens to hay fields, crops, and turf grass? Will they grow earlier or will they be privy to a freezing/thawing pattern early in the season that impedes their growth? (i.e."erratic springtime-in-the-Rockies")
- Mid-summer droughts resulting in agricultural losses and costly turf loss
- Enforcement of the state's 10-year abandonment list will require users to utilize their full water allotment and increase the need for more costly record keeping
- Less early-season, natural snowfall when ski areas are trying to open will result in the need to make more snow
- An increase in temperatures during November/early December may prevent ski areas from making snow until temperatures drop later in the season. Ski areas will be forced to make the same amount of snow in a shorter period of time, resulting in higher energy costs, more intense usage of water in a short period of time, and increased labor costs and
- Many of the above mentioned concerns could be very costly

Possible adaptations:

- Create more storage to capture water during peak flows to be used during low flow periods
- Put liners in the stock ponds so storage water is not lost to ground seepage
- Better irrigation ditch maintenance so water is not wasted
- Keep upstream users with more junior rights in check so that water is available to the downstream senior rights holders
- Use full allotment of water so rights are not lost on the state's ten year abandonment list;
- Sell cattle herds earlier in the season when there is not enough water to keep the hay green
- Place conservation easement on land to secure future water rights
- Implement better turf management techniques like balancing fertilizer use with water availability and using drought resistant turf
- Implement new irrigating technologies or hand water the turf to be more specific with water application
- Prioritize water-use in times of shortage
- Downscale or increase staff as needed (i.e. the golf course may need to employ more people to water turf by hand, but if business is too slow due to lack of water, staff may need to be decreased)
- The ski area could expand its existing snowmaking system to cover more area on the mountain in a shorter time period. This would require more staff to operate the snowmaking equipment
- Or the ski area could switch to a more expensive, yet more efficient, automatic snow making system that would require less staff to make the snow in a shorter period of time

RECREATIONAL/ INSTREAM USERS: a whitewater rafting operation, and a fly fishing business

Current and future concerns voiced by the stakeholders:

- Diversions to the front range that would put water levels too low for whitewater rafting or too low for quality fish habitat
- Peak runoff earlier in the spring resulting in a shorter rafting season that starts earlier, at a time when there are few tourists in town
- Rafting companies will need to bus customers to the Colorado River if the water levels are too low on the Roaring Fork River. The result would be a higher cost to the business and the customer, as well as more fossil fuels burned
- "Dilution is the solution to pollution." Lower instream flows could result in a lowered water quality, resulting in decreased macro-invertebrate and fishery populations
- Lower water quantity means higher water temperatures, which hampers fish survival; and
- Less water also equates to less actual fish habitat

Possible adaptations:

- Smaller boats that can run in less water

- Advertising trips earlier in the season during the earlier peak runoff – possibly enticing tourists to go rafting when the conditions on the ski area are less than optimal

ECOLOGICAL STAKEHOLDERS: USFS hydrologist, an environmental scientist/ conservation group, and an environmental land steward

Current and future concerns voiced by the stakeholders:

- Water quantity & water quality (low flows result in increased concentration of pollution)
- Maintaining riparian corridors and in-channel habitat
- Loss of biodiversity in the watershed
- Lack of water supply and reduced ground water
- Unnatural changes in the hydrograph that disrupt the native ecology (flooding when there should not be flooding, causing erosion and stream instability, or lack of peak flows to recharge and flush the system)
- Increased snowmelt or rainwater runoff due to lack of soil percolation in developed areas
- Increases or decreases in streamflow that are sustained over several years, rather than expected natural variability between years
- Slugs of gravel and cobble moving unnaturally into the stream system when a diversion fails under high-water conditions. The gravel kills the trees and plants below – for many miles in some cases
- Flora and fauna will not be able to adapt to the projected changes by the year 2030 or 2100
- Peak runoff may come earlier in the spring when the plants and animals are unable to use it. Or, even if plants start to grow earlier in the spring, they may experience a drought at the other end of the season that could make it tough for the animals to fatten up for the winter
- The limitless demand for water in the west, but the water is a finite resource
- Lack of staff, funds, and time to properly monitor the rivers
- The need for more gage stations at key nodes to allow better management of instream flows on the river

6.5 CONCLUSION

Climate change is likely to noticeably affect runoff in the upper Roaring Fork River by the year 2030, with more dramatic effects evident by 2100. Peak runoff will shift to earlier in the melt season; by 2030, peak runoff is predicted to occur in May rather than June. However, the historical streamflow pattern of low winter flow with late spring to summer peak flow is expected to remain the same. In 2100, peak flow is still projected to occur in May rather than June, but there may be increased winter flow due to winter melt, and reduced early to mid-summer streamflow. Monsoon moisture may increase July and August flows by the year 2100. However, not all models project that July runoff will increase. Projections of total annual runoff volume, which is dictated by total precipitation and loss due to evapotranspiration, are less certain than projected alterations in seasonal pattern (which are driven by temperature changes). But annual precipitation changes are projected to be fairly minor. Changes in total runoff should also be modest, but vary among the scenarios. Therefore, we are confident that there will be a shift in the timing of monthly runoff patterns, but are less confident in projections of annual runoff volumes.

Water users in the upper Roaring Fork basin have adapted to the seasonal flow pattern, and some would be affected more than others by a shift in peak flow. Reflecting the manifold of water stakeholders common in the West, the basin hosts a significant municipal system employing a mix of runoff and groundwater, agricultural users who rely on runoff for irrigation, dispersed rural residential users, diversions to other watersheds, and required flows for endangered species. The basin's economy is closely tied to the recreation and tourism sector that employs water for snowmaking, whitewater sports, fishing, irrigation of golf greens, and aesthetics. Ecological conditions in the Roaring Fork are closely tied to runoff, and are already stressed by lower-than-optimal flows. Changes in the timing of flows throughout the year could cause even greater ecological impacts. In short, water is crucial to regional well-being, and any climate-induced changes in runoff are worrisome.

> An earlier peak and lower flows may dramatically curtail whitewater recreation.

Demand for water could rise in summer, forcing agricultural interests to take more of their allotments, which would leave less water in the river for other users. The municipal system has relatively small storage compared to its demand and therefore could experience shortages if runoff were to occur over a shorter period of time. Warmer temperatures also raise the water demands for irrigated crops, golf courses, and landscaping, and they stress aquatic habitat as well.

Stakeholders in the upper Roaring Fork basin also worry about institutional and political changes that could affect water supply. The upper Roaring Fork is subject to senior water rights demands from downstream users. The basin's own population is growing rapidly, as is population in nearby basins. The upper Roaring Fork is part of the contested Colorado Basin, and would be affected by any changes in the Colorado River Compact or other re-allocations. Indeed, basin stakeholders appear more concerned about institutional uncertainty than climate uncertainty.

So, how does all this add up? How vulnerable is the upper Roaring Fork to global warming? The answer is elusive, but a few insights come out of this study. First, the basin is awash in uncertainty. Rapid population growth, growing in-basin demands (which would be exacerbated if global warming raises overall temperatures and makes snowmaking and summer irrigation more demanding), and pressures from outside the upper Roaring Fork all point to increased competition for supply, which would reduce runoff (though some outside demands might actually *increase* instream flows by requiring more water be sent to downstream users). Dry conditions in 2002 already exposed regional vulnerability, but also revealed some flexibility in the system. Informal agreements among users maintained minimum streamflow, and water users in the basin report that actual use is both more complicated than, and different from, the "decreed" allocation of basin supplies on paper. Yet, users also worry that these flexibilities will be squeezed out of the system by "raids" on water and water rights, and the inexorable logic of western water law that each user must use, or lose, their allotment.

On paper, the river could be dried up in most years, and will be if each water rights holder seeks to maximize its use. These trends clearly point to increasing vulnerability, though it is difficult to discern whether the basin is near some tipping point in which climate change could substantially degrade the water resource. In any case, the clear message of this study is that water management in the basin must be examined in light of likely tightening supplies. Policies that reduce flexibility are maladaptive in the face of an uncertain climate change future.

Water management in the basin must be examined in light of likely tightening supplies. Policies that reduce flexibility are maladaptive in the face of an uncertain climate change future.

BRIEF DESCRIPTION OF A1 AND B1 SRES SCENARIOS

The A1 storyline, in general, assumes strong economic growth and liberal globalization characterized by low population growth, very high GDP growth, high-to-very high energy use, low-to-medium changes in land use, medium-to-high resource availability (of conventional and unconventional oil and gas), and rapid technological advancement. The A1 scenario assumes convergence among regions, including a substantial reduction in regional differences in per capita income in which the current distinctions between "poor" and "rich" countries eventually dissolves; increased capacity building; and increased social and cultural interactions. A1 emphasizes market-based solutions, high savings, and investment, especially in education and technology, and international mobility of people, ideas, and technology.

The A1 storyline is broken up into groups that characterize alternative developments of energy technologies. A1FI represents the "fossil intensive" scenario and results in the highest emissions and the highest atmospheric concentrations of carbon dioxide (Schröter, 2005). The A1B scenario represents a "balanced" development of energy technologies. It assumes that no one energy source is relied on too heavily and that similar improvement rates apply to all energy supply and end use technologies (IPCC, 2000a).

The B1 scenario describes a convergent world that emphasizes global solutions to economic, social, and environmental sustainability. Focusing on environmental sensitivity and strong global relationships, B1 is characterized by low population growth, high GDP growth, low energy use, high changes in land use, low resource availability of conventional and unconventional oil and gas, and medium technological advancement. The B1 scenario assumes rapid adjustments in the economy to the service and information sectors, decreases in material intensity, and the introduction of clean and resource-efficient technologies. A major theme in the B1 scenario is a high level of environmental and social consciousness combined with a global approach to sustainable development.

APPENDIX B

SDSM CALIBRATION FOR INDEPENDENCE PASS

NCEP Predictor Variables

Predictand	Predictors (NCEP re-analysis)	Partial *r*
TAVG	Mean regional temperature at 2m	0.93
	Near surface zonal wind component	-0.43
	Meridianal wind component at 500 hPa level	0.23
	Near surface relative humidity	0.20
PRCP	Relative humidity at 500 hPa level	0.19
	Near surface meridianal wind component	0.12
	Mean regional temperature at 2m	-0.08
	Mean sea level pressure	-0.07
	Airflow strength at 500 hPa level	0.06
	850 hPa geopotential height	0.01

TABLE B.1: **NCEP predictor variables for a domain centered on Independence Pass.**

Example Predictor-Predictand Relationships

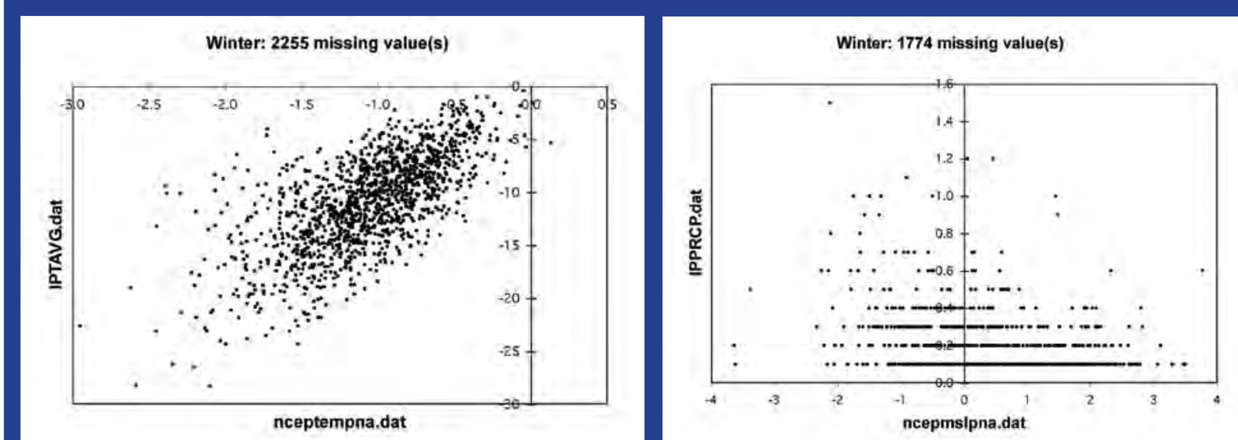


FIGURE B.1: **Example predictor-predictand relationship for winter (DJF) TAVG and near surface regional temperatures (left); PRCP and mean sea level pressure (right).**

Lag-1 Autocorrelation and Cross-Correlation, 1986-2000

	Observed		SDSM	
	TAVG	PRCP	TAVG	PRCP
Lag-1 r	0.938	0.236	0.882	0.167
Cross r	-0.075		-0.068	

TABLE B.2: Lag-1 autocorrelation and cross-correlation for TAVG and PRCP 1986-2000.

INDEPENDENCE PASS DAILY AVERAGE TEMPERATURE (TAVG)

Independence Pass TAVG Dec 1999 to Apr 2000

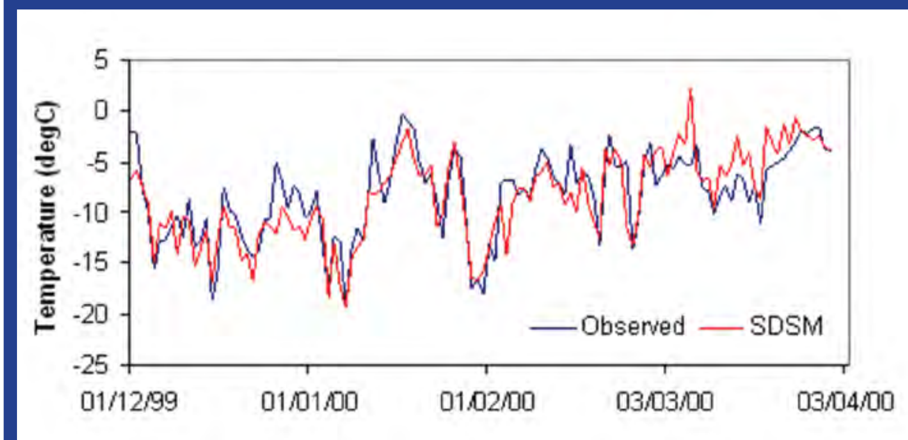


FIGURE B.2: Illustration of daily time-series behavior: comparison of downscaled and observed TAVG for the winter of 1999/2000.

Independence Pass TAVG 1986-2000

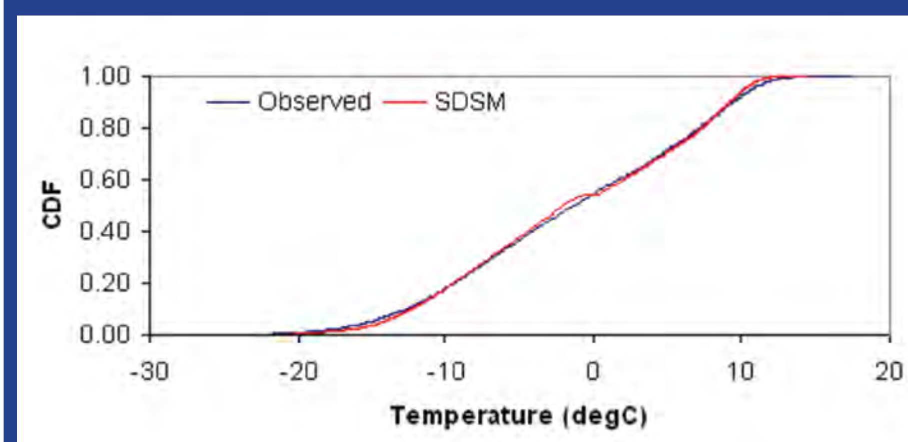


FIGURE B.3: Illustration of cumulative distribution function (CDF): comparison of downscaled and observed daily TAVG for 1986-2000.

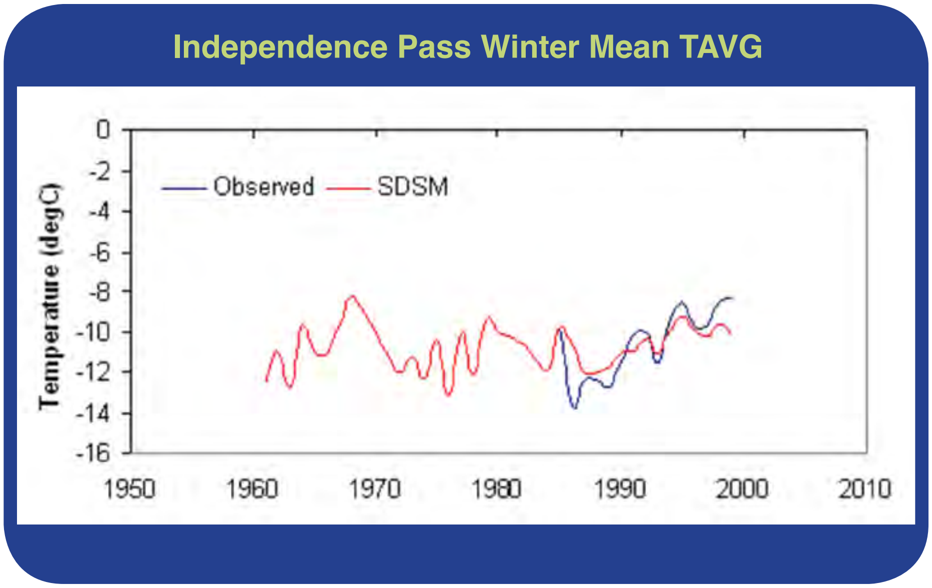


FIGURE B.4: **Observed and downscaled annual mean winter TAVG.** Note that the downscaling was performed using large-scale NCEP predictor variables 1961-2000.

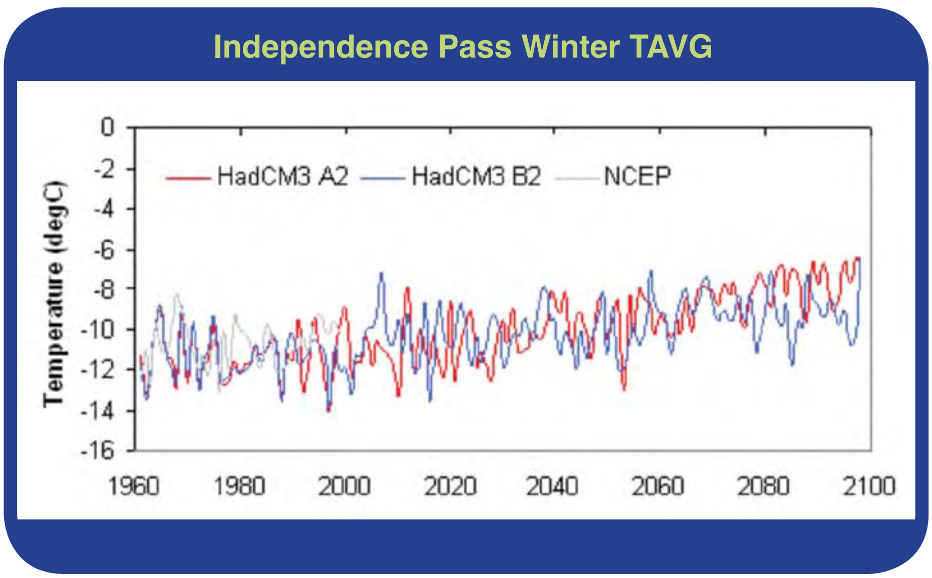


FIGURE B.5: **Downscaled annual mean winter TAVG 1961-2099 compared with the NCEP control run 1961-2000.**

Changes in Seasonal Mean TAVG

	DJF		MAM		JJA		SON	
	A2	B2	A2	B2	A2	B2	A2	B2
2020s	1.0	1.0	0.7	0.7	1.3	1.6	1.1	1.3
2050s	2.1	1.6	1.3	1.3	2.6	2.4	1.8	2.0
2080s	3.6	2.2	2.5	1.5	4.0	2.9	3.1	2.7

TABLE B.3: **Changes in seasonal mean TAVG (°C) for HadCM3, A2 and B2 emissions.**

INDEPENDENCE PASS DAILY PRECIPITATION (PRCP)

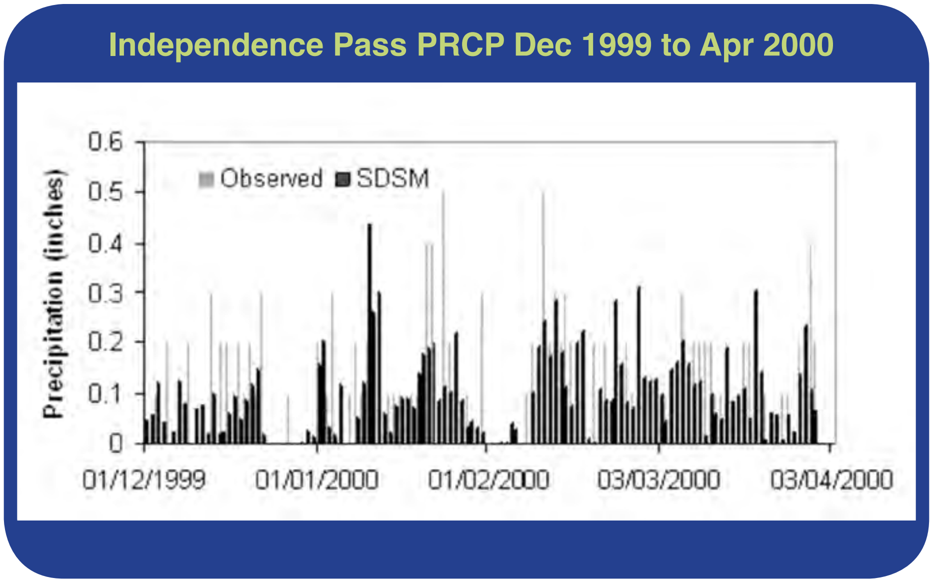


FIGURE B.6: **Illustration of daily time-series behavior: comparison of downscaled and observed PRCP for the winter of 1999/2000.**

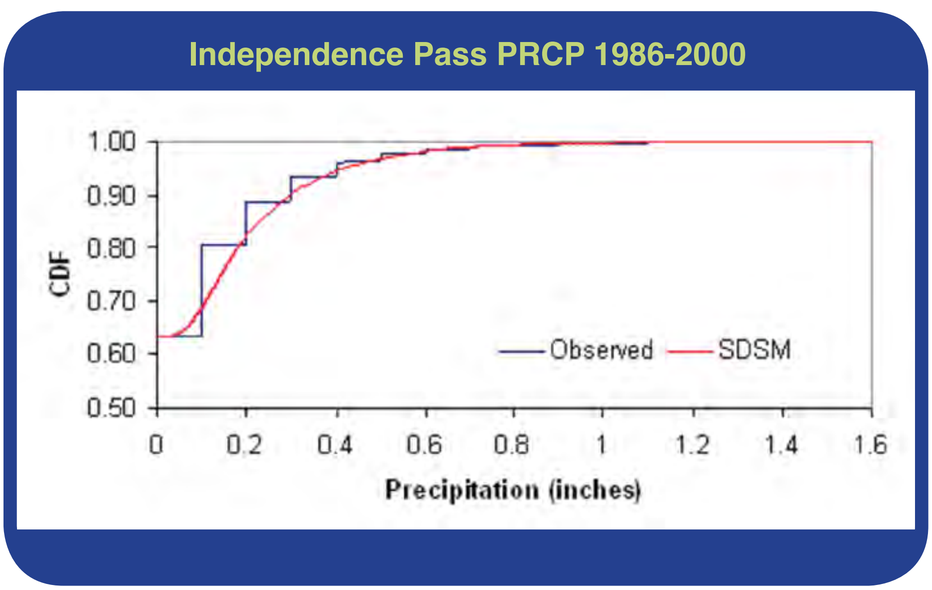


FIGURE B.7: **Illustration of cumulative distribution function (CDF): comparison of downscaled and observed daily PRCP for 1986-2000.** Note that SDSM correctly captures the fraction of dry-days (~63%).

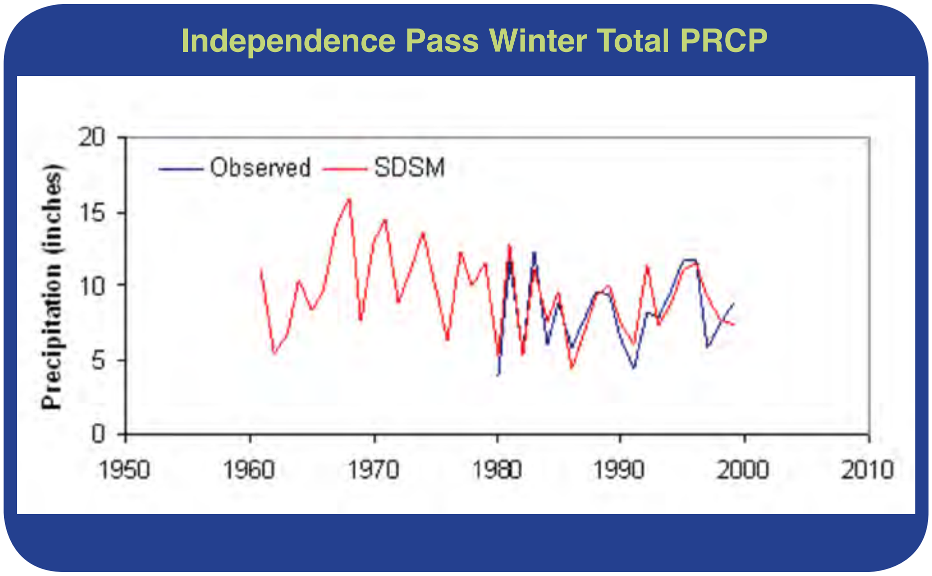


FIGURE B.8: **Observed and downscaled annual winter PRCP.** Note that the downscaling was performed using large-scale NCEP predictor variables 1961-2000.

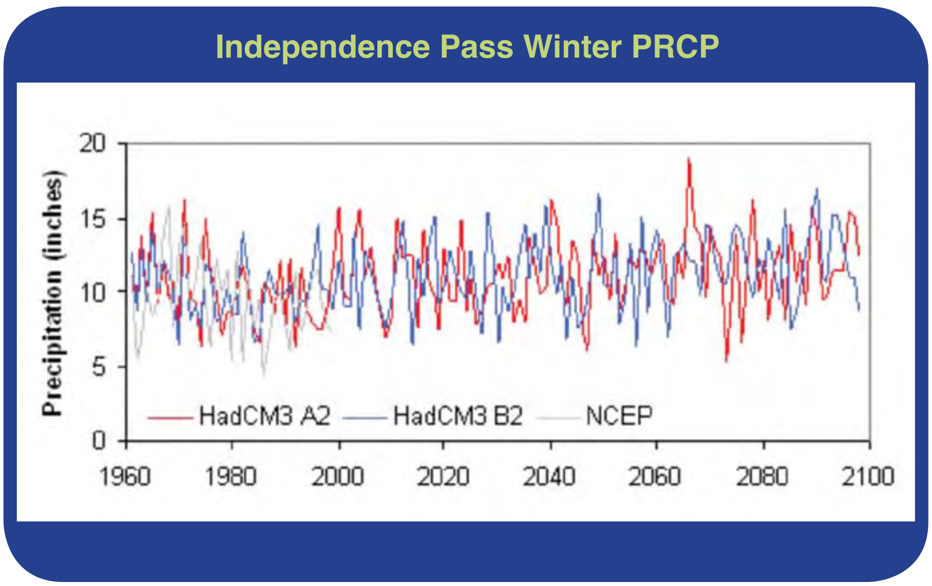


FIGURE B.9: **Downscaled annual winter PRCP 1961-2099 compared with the NCEP control run 1961-2000.**

Changes in Seasonal Total PRCP

	DJF		MAM		JJA		SON	
	A2	B2	A2	B2	A2	B2	A2	B2
2020s	8.6	11.8	-14.1	-8.7	-10.2	-15.8	-5.9	-7.0
2050s	15.7	9.9	-24.8	-15.2	-5.4	-4.0	-10.6	-9.0
2080s	14.4	18.4	-34.9	-19.6	8.8	-6.7	-22.6	-19.5

TABLE B.4: **Changes in seasonal total PRCP (%) for HadCM3, A2 and B2 emissions.**

PCMDI PROBABILITY DISTRIBUTIONS FOR ASPEN

Our Bayesian statistical model synthesized the information contained in an ensemble of different PCMDI (Program for Climate Model Diagnosis and Intercomparison) GCMs, run under historical and future scenarios, into Probability Distribution Functions (PDFs) of temperature and precipitation change. Table C.1 presents probability density functions for regional projections from 21 GCMs on temperature and 20 GCMs on precipitation under the A1B emissions scenario. The probability density functions are organized from low temperatures and decreased precipitation to higher temperatures and less decreases to increases in precipitation.

Historical observed data are used to assess model reliability in representing current climate. In addition, the criterion of "convergence" bears weight in determining how individual GCMs contribute to the overall estimate, in the sense that projections that agree with one another within the ensemble will receive relatively more weight in the final estimates of the PDFs than projections that appear as outliers.

Our analysis was performed at a regional scale, i.e. we first area-averaged the 4 gridpoints surrounding Aspen (covering the area from 105.50-111.06°W and 36.30-41.84°N), for each GCM contributing data, into regional means of temperature and precipitation. Then the individual models' projection were combined. Ultimately, for each season and for each SRES scenario (A2 = high emissions, A1B = mid-range emissions and B1 = low emissions) we determined as our final output Probability Distribution Functions (PDFs) of temperature and precipitation change ("change" is defined as the difference between two 20-year means, e.g. 1980-99 vs. 2080-99) (Table C.2, Figures C.2-5).

Probability Density Functions for GCM output near Aspen

Time period	PDF	Temperature change (°F)	% Precipitation change
2030	0.05	0.67	-26.25
	0.25	1.89	-11.01
	0.50	2.75	-2.11
	0.75	3.58	7.28
	0.95	4.84	21.24
2090	0.05	4.61	-25.99
	0.25	5.99	-11.95
	0.50	6.95	-2.89
	0.75	7.79	7.62
	0.95	9.09	21.68

TABLE C.1: **Probability density functions for GCM output near Aspen under the A1B emissions scenario.**

The 50th percentile (median) warming is about 1°F (0.5°C) lower than the mean warming we are using from MAGICC/SCENGEN. The difference could be a function of the climate sensitivity chosen for the analysis. It may also be the choice of the GCMs or the geographic area The five models used in MAGICC/SCENGEN all project decreased precipitation, the precipitation change for A1B early and late century also show decreases although the decrease is minor (Table C1). The PCMDI multimodel runs show increased precipitation in the winter, decreases in the spring and summer, and mixed results in the fall for early mid and late century results (Table C.2).

Figure C1 shows how a shift in the mean or variance or both alters the likelihood of extreme events. It is used here as a guide for interpreting the probability distribution functions comparing different emission scenarios in Figures C.2 and C.3 and in comparing seasons in Figures C4 and C5. Note that all the scenarios used in C.2 and C.3 have A2 as the high scenario compared to the MAGICC/SCENGEN runs that used A1FI. Also note that Figures C.4 and C.5 are just for the high scenario A2.

In C.4, as the century progresses, the seasons diverge, with the summer increasing the most and the winter the least. In C.5 the variance for the summer months remains high. The variance for spring precipitation remains low and there is a divergence where the winter gets wetter and the spring drier.

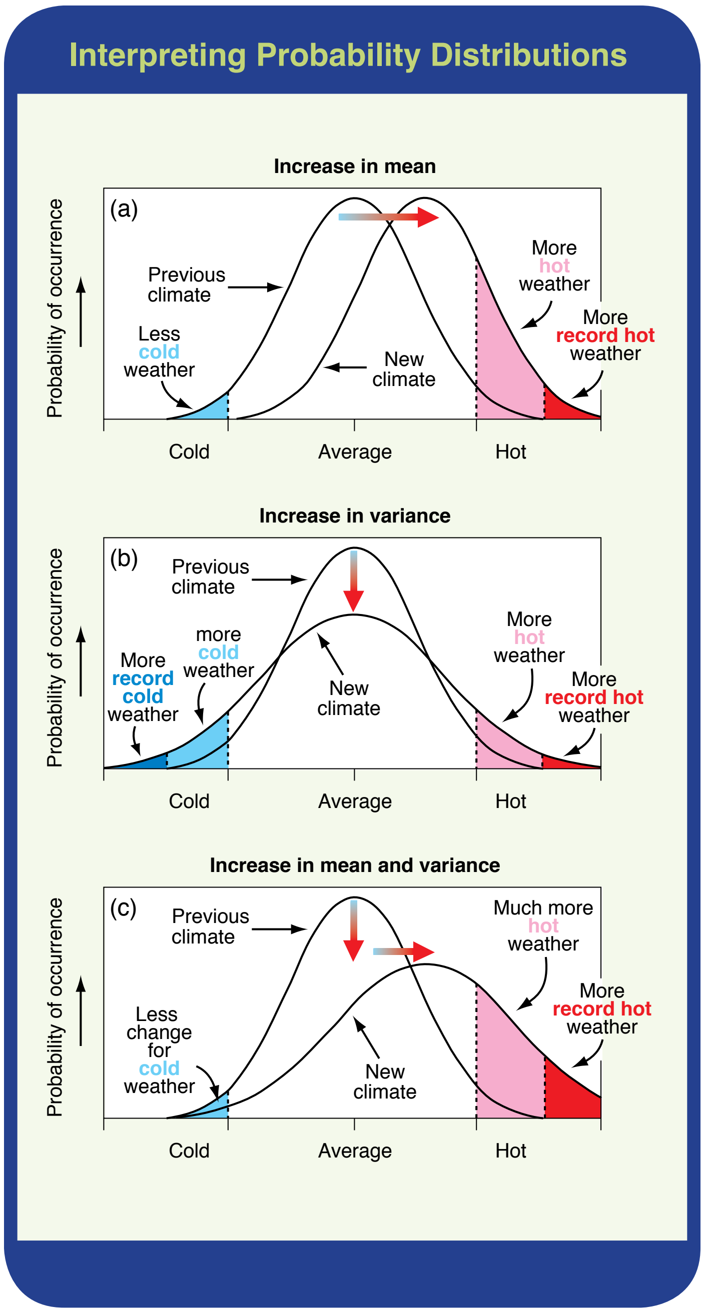


FIGURE C.1: **Illustration of the significance of a change in mean and/or variance in relation to the likelihood of extremes.** This schematic from the IPCC Third Assessment Report shows the effect on extreme temperatures when (a) the mean temperature increases, (b) the variance increases, and (c) when both the mean and variance increase for a normal distribution of temperature. (Source: Figure 2.32 from IPCC, 2001a)

Median PDF Values

TEMPERATURE

B1 Temperature Change (°F)				
Time Period	DJF	MAM	JJA	SON
2000-2020	1.4	1.1	1.4	1.3
2040-2060	2.9	2.9	3.6	2.9
2080-2100	4.7	4.3	5.4	4.5

A1B Temperature Change (°F)				
Time Period	DJF	MAM	JJA	SON
2000-2020	1.1	1.1	1.4	1.3
2040-2060	3.8	4.1	5.2	4.3
2080-2100	6.5	6.5	8.1	6.8

A2 Temperature Change (°F)				
Time Period	DJF	MAM	JJA	SON
2000-2020	1.1	1.1	1.4	1.4
2040-2060	3.6	3.8	4.9	4.0
2080-2100	7.4	8.1	9.9	8.5

PRECIPITATION

B1 Precipitation Change (% of 1980-1999 average)				
Time Period	DJF	MAM	JJA	SON
2000-2020	4.5	-0.9	-4.8	-0.1
2040-2060	3.9	-1.4	-5.5	2.6
2080-2100	5.9	-2.2	-4.5	0.6

A1B Precipitation Change (% of 1980-1999 average)				
Time Period	DJF	MAM	JJA	SON
2000-2020	2.5	-1.9	-4.1	-0.7
2040-2060	6.7	-4.7	-8.2	0.6
2080-2100	10.4	-7.5	-10.7	-0.5

A2 Precipitation Change (% of 1980-1999 average)				
Time Period	DJF	MAM	JJA	SON
2000-2020	4	-0.7	-7.6	0
2040-2060	9.3	-6.1	-7.4	2.1
2080-2100	11.8	-15.7	-8.4	6.3

TABLE C.2: **Median PDF values for seasonal temperature and precipitation for GCM output near Aspen, shown for early, mid, and late 21st century.** (Source: Data provided by by C. Tebaldi and L. Mearns at NCAR utilizing data from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) IPCC Data Archive at Lawerence Livermore National Laboratory. Tebladi et al., 2004; Tebaldi et al. 2005)

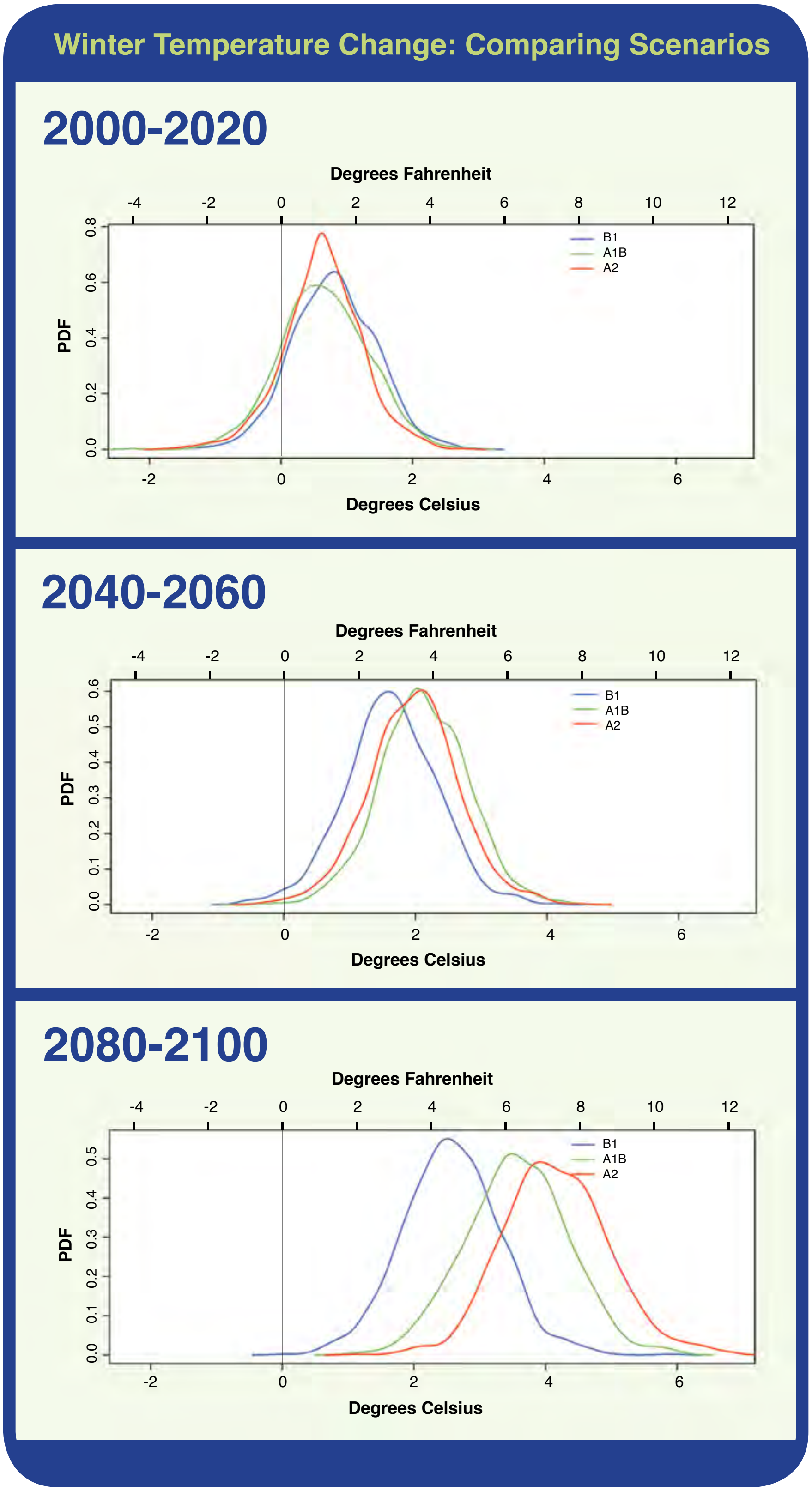


FIGURE C.2: **Mean temperature change in Aspen in December-January-February, comparing B1, A1B, and A2 scenarios for the early, mid, and late 21st century.** Zero line represents no change in temperature; peaks further to the right indicate a greater increase in temperature for the scenario identified. Y-axis is a function of probability. (Source: Plots made for the Aspen project by C. Tebaldi and L. Mearns at NCAR utilizing data from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) IPCC Data Archive at Lawerence Livermore National Laboratory. Tebladi et al., 2004; Tebaldi et al. 2005)

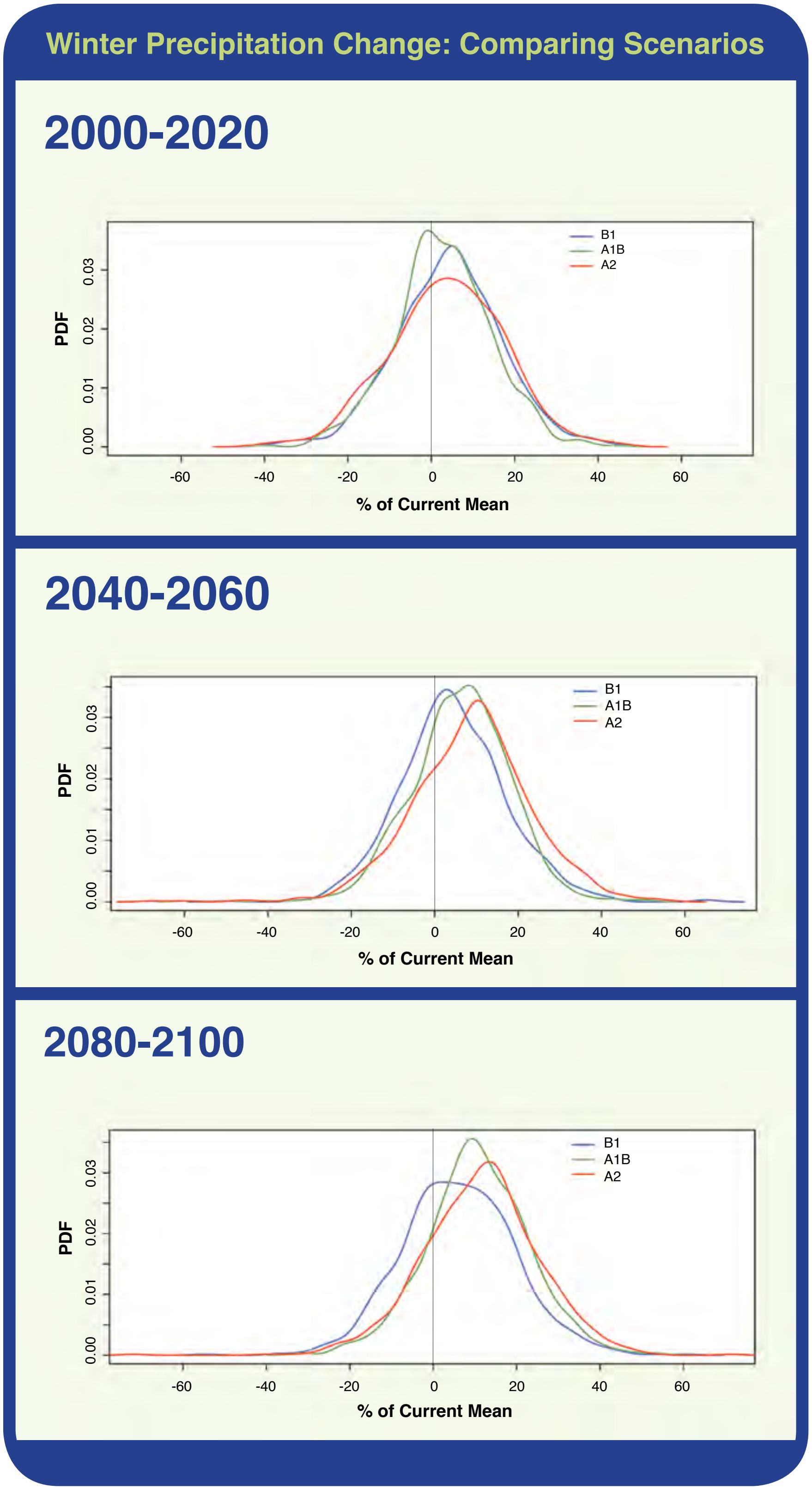


FIGURE C.3: **Mean precipitation change in Aspen in December-January-February, comparing B1, A1B, and A2 scenarios for the early, mid, and late 21st century.** Zero line represents no change in precipitation; peaks to the right of zero indicate an increase in precipitation for the scenario identified, while peaks to the left indicate a decrease. Y-axis is a function of probability. (Source: Plots made for the Aspen project by C. Tebaldi and L. Mearns at NCAR utilizing data from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) IPCC Data Archive at Lawerence Livermore National Laboratory. Tebladi et al., 2004; Tebaldi et al. 2005)

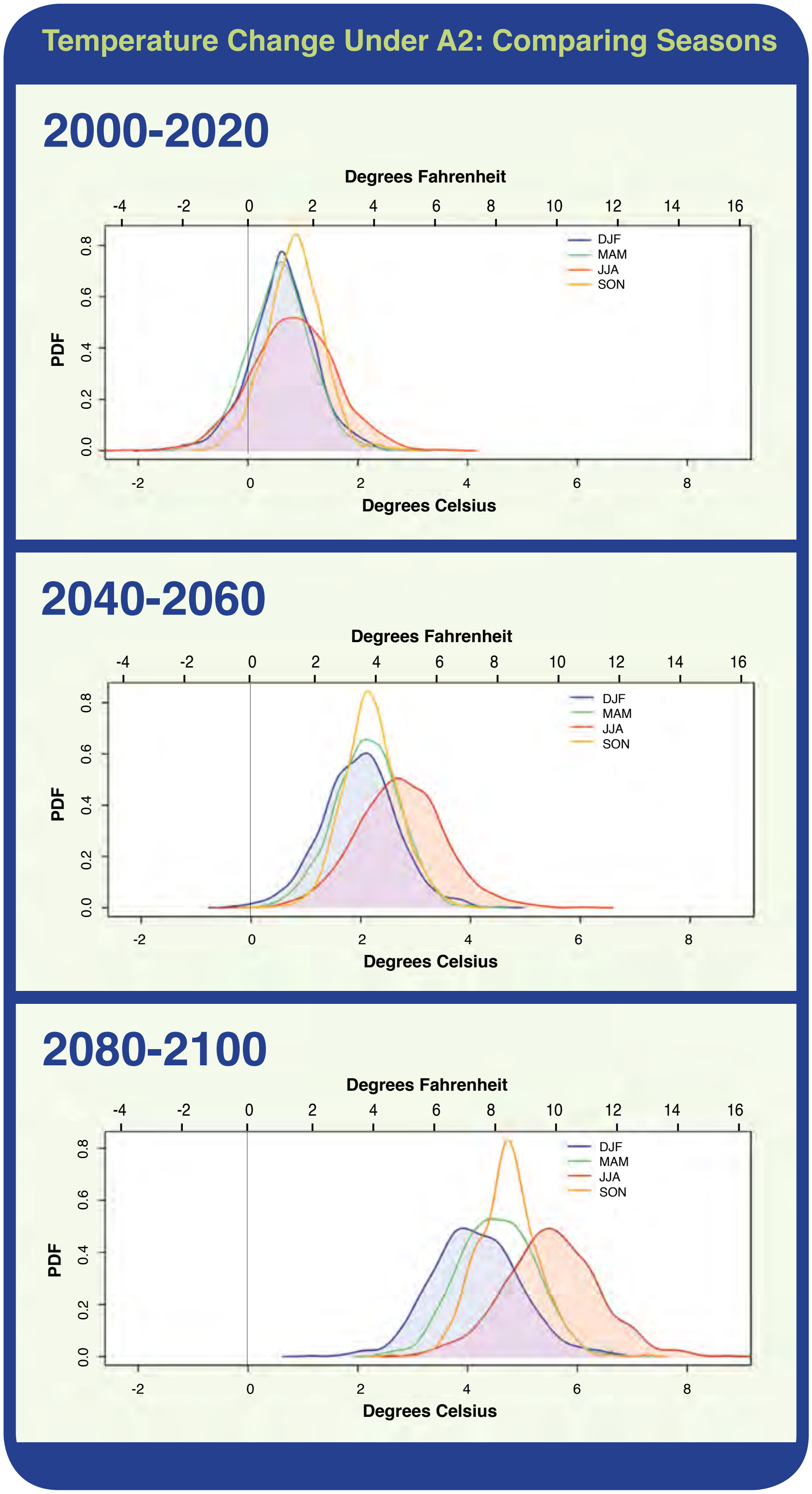


FIGURE C.4: **Mean temperature change in Aspen under the A2 scenario, comparing seasons for the early, mid, and late 21st century.** Zero line represents no change in temperature; peaks further to the right indicate a greater increase in temperature for the months identified. Y-axis is a function of probability. Shaded plots suggest greater warming in summer (red) vs. winter (blue) months. (Source: Plots made for the Aspen project by C. Tebaldi and L. Mearns at NCAR utilizing data from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) IPCC Data Archive at Lawerence Livermore National Laboratory. Tebladi et al., 2004; Tebaldi et al. 2005)

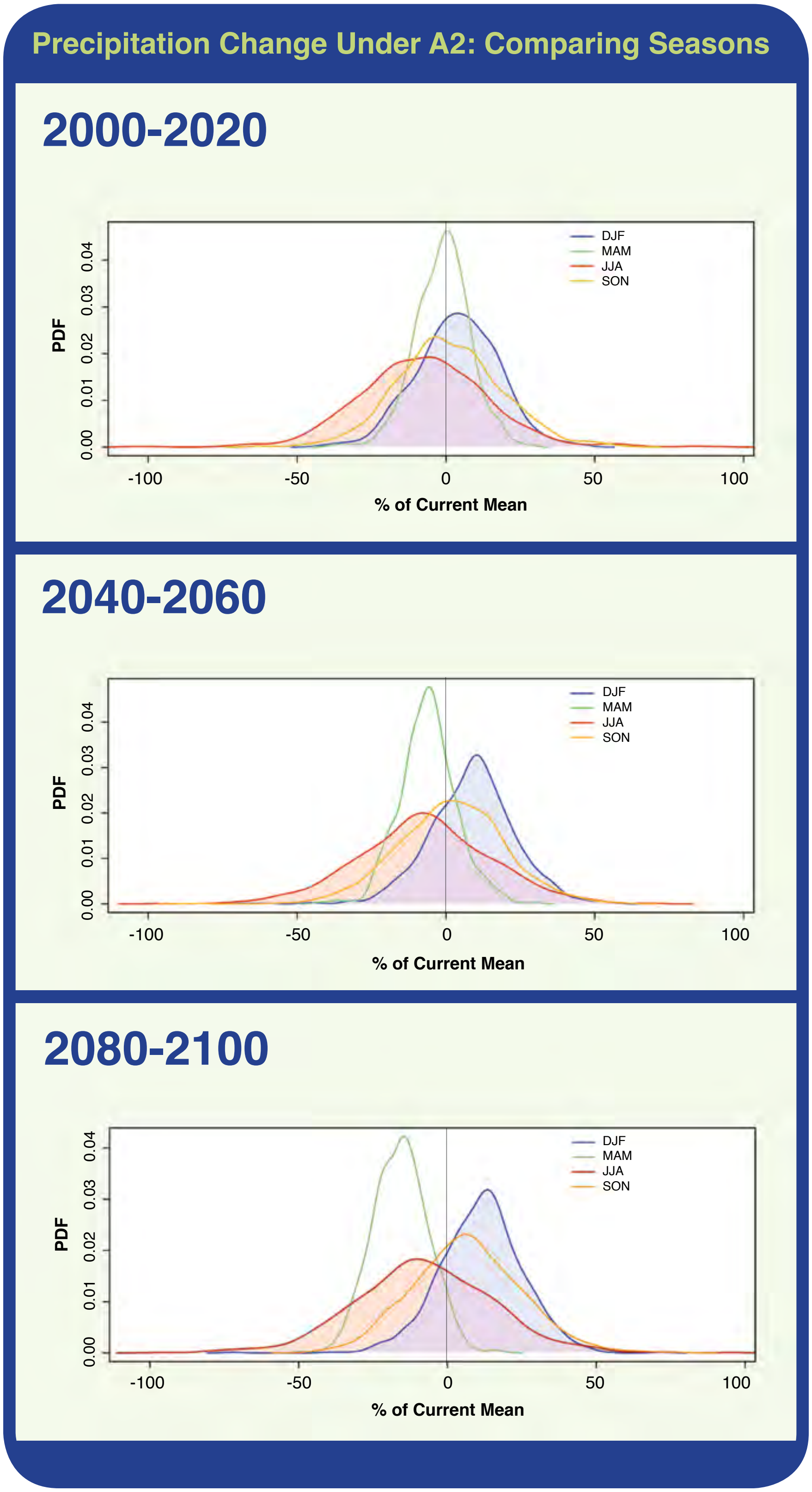


FIGURE C.5: **Mean precipitation change in Aspen under the A2 scenario, comparing seasons for the early, mid, and late 21st century.** Zero line represents no change in precipitation; peaks to the right of zero indicate an increase in precipitation for the months identified, while peaks to the left indicate a decrease. Y-axis is a function of probability. (Source: Plots made for the Aspen project by C. Tebaldi and L. Mearns at NCAR utilizing data from the Program for Climate Model Diagnosis and Intercomparison (PCMDI) IPCC Data Archive at Lawerence Livermore National Laboratory. Tebladi et al., 2004; Tebaldi et al. 2005)

ASSESSING THE SKILL OF CLIMATE MODELS (AOGCMS)

Tom Wigley

National Center for Atmospheric Research,
Boulder,
CO 80307-3000

June 15, 2005

Introduction

This report is concerned with the use of coupled Atmosphere/Ocean GCMs (AOGCMs) to estimate future changes in climate at a regional scale. There are two issues: whether the current suite of models is credible; and whether, if so, some models are better than others. If the latter is correct, then one might argue that only the sub-set of better models should be used for future projections.

To assess AOGCMs, the simplest (and standard) method is to see how well a particular model can reproduce the details of present-day climate. There is a large body of literature on this subject that I will not attempt to review. The most important activities are the co-ordinated, multi-variate model assessment and intercomparison studies being undertaken at PCMDI/LLNL under two programs, AMIP and CMIP. Results from these studies have, deliberately, never been used to rank models in terms of their perceived skill. There are many reasons for this – but one of the most important is that a model that is most skillful for one variable may well be far less skillful for another. Some interesting paradoxes have arisen in this regard – for example, a model that is skilful in simulating present-day precipitation may not be so skillful in simulating present-day cloud patterns and amounts. The message to be learned here is that assessing model skill is an extremely difficult and complex task. One should therefore be wary of the results of any limited assessment (including the present one).

Another important issue is that, just because a particular model is able to simulate present-day climate better than another does not mean that its predictions of future climate will necessarily be better.

To provide some insights into relative model skill, some results from the MAGICC/SCENGEN software package are described below. Note that this is far from being a comprehensive assessment. MAGICC/SCENGEN is easy to use and any interested reader can use it to expand upon the results given here.

The two main tools that can be used are: (1) the ability to display maps of model errors, which show the differences between present day control run results and present day observed climate, and (2) output in the VALIDN file that compare these pattern is statistical terms. These comparisons can be done for any of the 17 AOGCMs in the SCENGEN data base, or any combination of these models, for either precipitation or temperature, for monthly, seasonal or annual-mean data, and for any region selected by the user.

Results

Spatial maps of 'error' show the temperature errors as a difference (Model (M) minus Observations (O)) and the precipitation errors as a percentage (100(M/O – 1)). Figure D.1 shows annual-mean temperature errors averaged over 16 models. Over the western US, models (on average) perform well, with errors less than 1C.

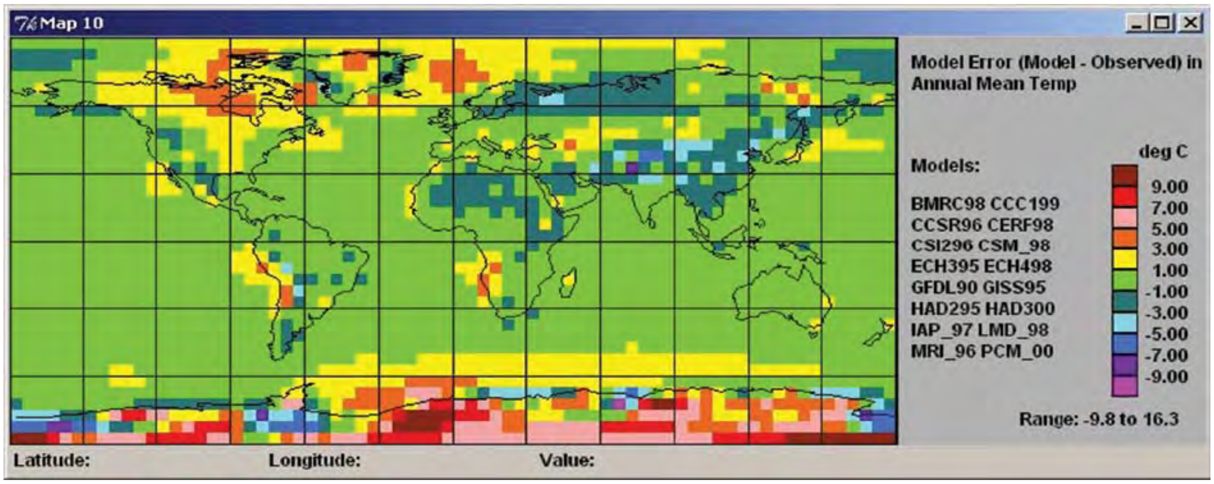


FIGURE D.1: **Annual mean temperature errors, averaged over 16 models.**

MODEL	CORREL	RMSE (°C)	MEAN DIFF (°C)	NUM PTS
BMRCTR	.985	3.042	-1.631	2592
CCC1TR	.983	2.642	-.264	2592
CCSRTR	.982	2.785	-.578	2592
CERFTR	.985	3.855	-2.760	2592
CSI2TR	.988	2.464	**.198**	2592
CSM_TR	.990	2.409	1.287	2592
ECH3TR	.987	2.531	-.971	2592
ECH4TR	.995	**1.679**	-.644	2592
GFDLTR	.987	3.522	2.376	2592
GISSTR	.985	2.556	-.394	2592
HAD2TR	.995	**1.578**	.435	2592
HAD3TR	.994	**1.779**	.462	2592
IAP_TR	.982	3.706	**.138**	2592
LMD_TR	.959	4.437	**.027**	2448
MRI_TR	.986	3.072	-1.515	2592
PCM_TR	.991	2.627	1.720	2592
MODBAR	.996	1.455	-.133	2592

TABLE D.1: **16 models : Variable = TEMP : Season = ANN.** Model validation: comparing model baseline with observed data. Area specified by mask. Maskfile = MASK.A : Maskname = GLOBE. Cosine weighted statistics.

Individual model results, or results for particular seasons, can also be easily generated. Table D.1 below shows individual model results that come from the SCENGEN output file VALIDN.OUT. Note that the MEAN DIFF column is observed minus model (opposite order from that used in the maps). These results are for the area average over the chosen region (here, the globe).

It can be seen that all model give high pattern correlations over the globe for model versus observed temperature. This is not so difficult – it mainly reflects the models' skill in getting high latitudes cold and low latitudes warm. There are substantial root mean square errors (RMSE). Models also show overall biases, from being too cold to being too warm. Models with the least bias are not the same as those with the smallest RMSE (see items in blue). (The last line in Table 1 shows the performance of the model average. Averaging over all models usually gives better results than for any individual model.)

I will now turn to precipitation. Figure D.2 shows the same result as Figure D.1 for precipitation, but the errors are much larger. In general, there is a bias with models giving too much precipitation over the western US.

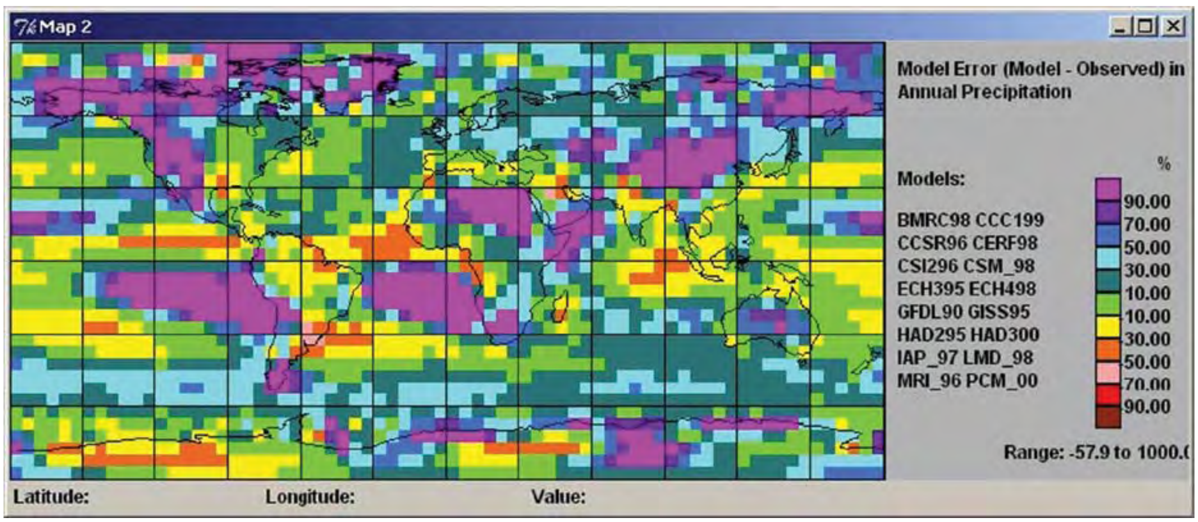


FIGURE D.2: **Annual mean precipitation errors, averaged over 16 models.**

This precipitation bias varies from model to model, but a positive bias is common to most models. Figures D.3, D.4 and D.5 show results for a few individual models. Over the western US the biases are: HadCM3, strong positive bias; ECHAM4, weaker but still positive bias; and CSM2, strong positive bias.

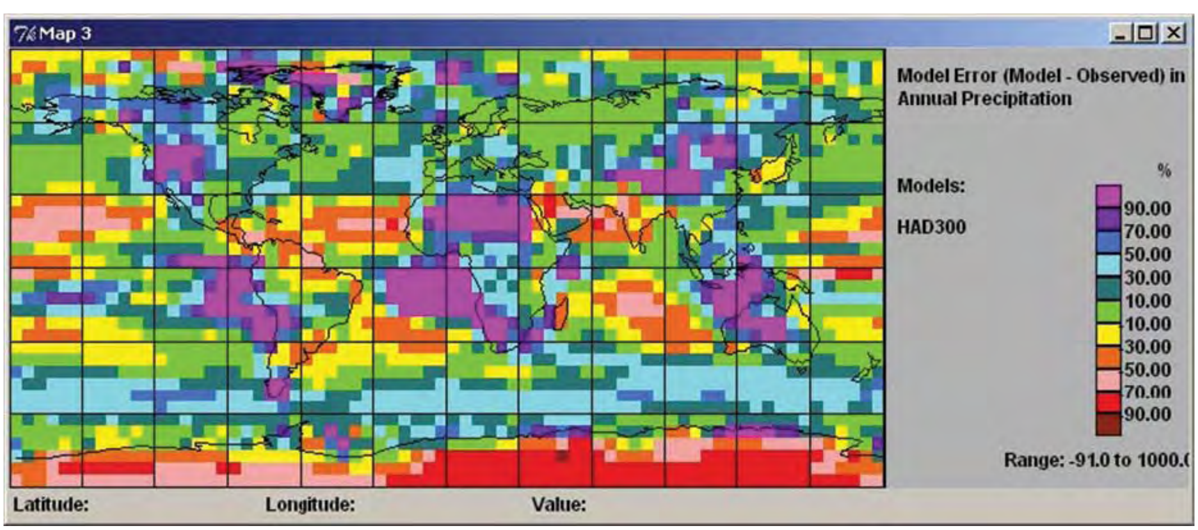


FIGURE D.3: **Annual mean precipitation error for HadCM3 (UK Hadley Centre).**

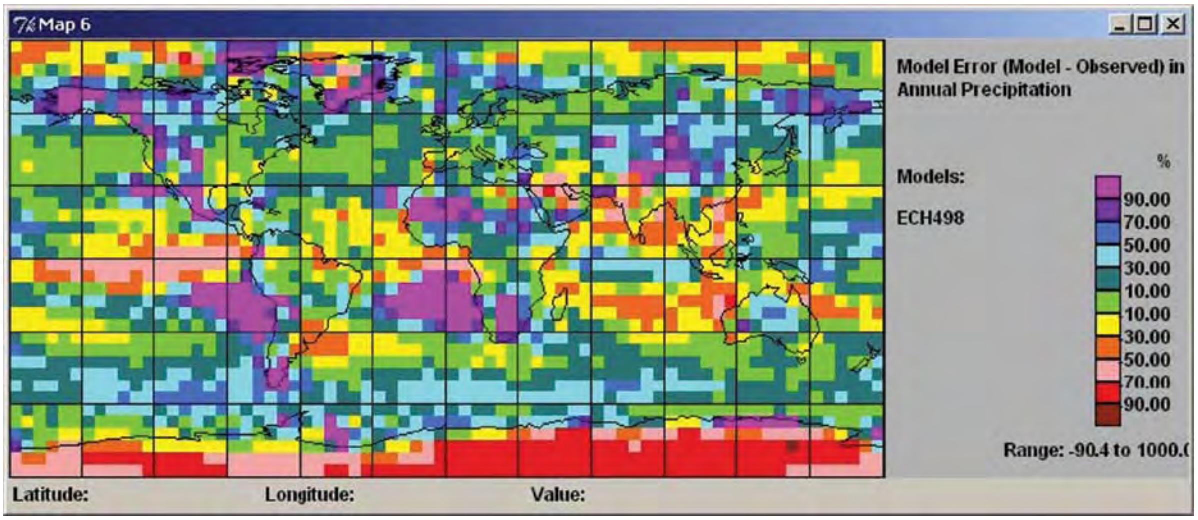


FIGURE D.4: **Annual mean precipitation error for ECHAM4 (Max Planck Institute, Germany).**

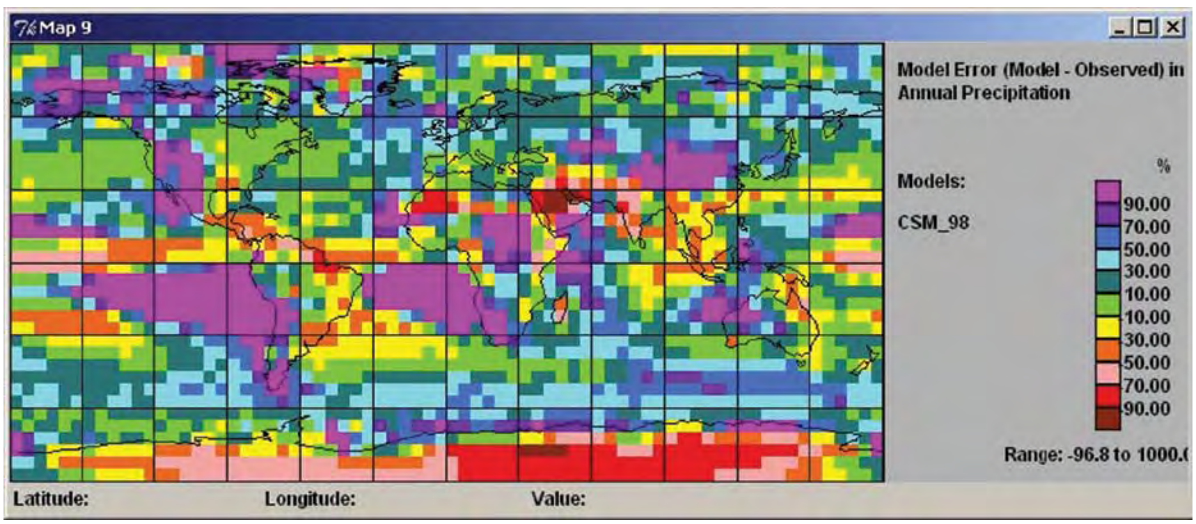


FIGURE D.5: **Annual mean precipitation errors for CSM2 (NCAR, Boulder, CO).**

These errors are common to the winter (DJF) in spring (MAM) seasons, as shown in Figures D.6 and D.7.

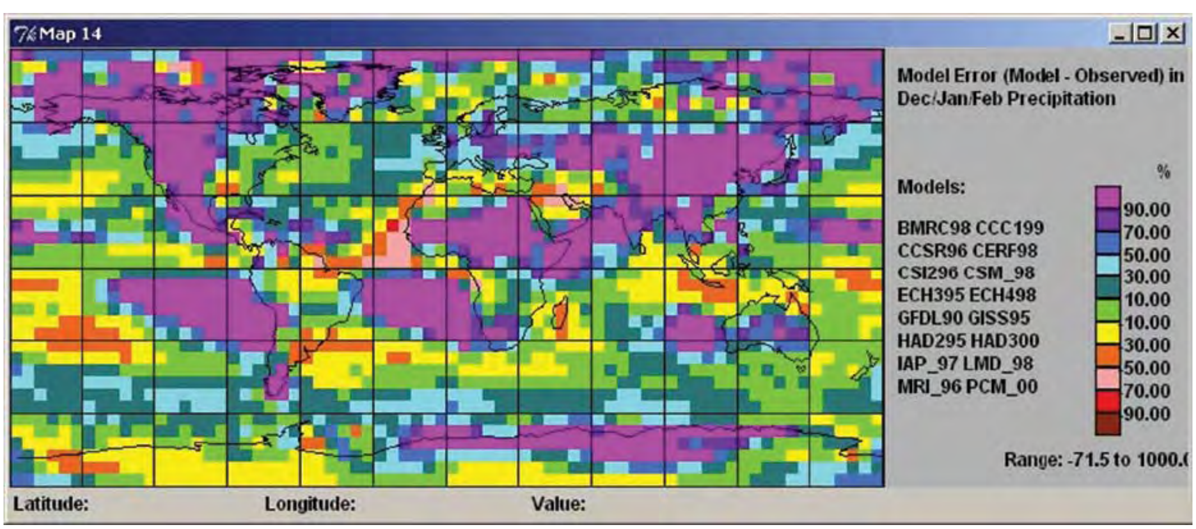


FIGURE D.6: **Precipitation errors for NH winter (DJF), averaged over 16 models.**

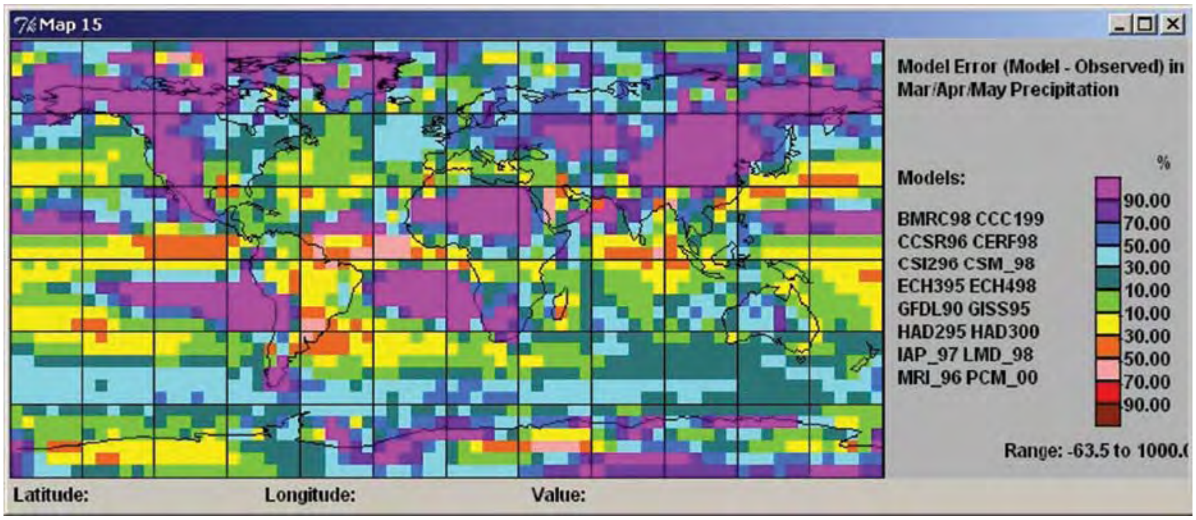


FIGURE D.7: **Precipitation errors for NH spring (MAM), averaged over 16 models.**

Whether or not these biases will be reflected in projected changes in precipitation is unknown. It should also be remembered that these results are for the penultimate generation of AOGCMs (as in the CMIP2 data base at PCMDI/LLNL). New versions of most of these models have been produced for use in the IPCC Fourth Assessment Report. Work is in progress in assessing this new generation of models and their results will be used in the next version of MAGICC/SCENGEN.

Individual model results may be generated as error fields, as in Figures D.3, D.4 and D.5, or may be viewed in the VALIDN.OUT output file. VALIDN.OUT results are shown in Table D.2.

MODEL	CORREL	RMSE mm/day	MEAN DIFF mm/day	NUM PTS
BMRCTR	.721	1.643	-.295	2592
CCC1TR	.715	1.529	-.119	2592
CCSRTR	.744	1.382	**.073**	2592
CERFTR	.802	1.277	-.364	2592
CSI2TR	.864	**1.037**	-.104	2592
CSM_TR	.785	1.411	-.370	2592
ECH3TR	.826	1.185	**-.061**	2592
ECH4TR	**.908**	**.936**	-.145	2592
GFDLTR	.736	1.400	**.051**	2592
GISSTR	.729	1.535	-.424	2592
HAD2TR	**.886**	**1.097**	-.378	2592
HAD3TR	**.870**	1.168	-.238	2592
IAP_TR	.660	1.679	.489	2592
LMD_TR	.686	1.623	-.207	2448
MRI_TR	.697	1.562	-.247	2592
PCM_TR	.670	1.688	-.357	2592
MODBAR	.915	.876	-.168	2592

TABLE D.2: **16 models : Variable = PRECIP : Season = ANN.** Model validation: comparing model baseline with observed data. Area specified by mask. Maskfile = MASK.A : Maskname = GLOBE. Cosine weighted statistics.

The three 'best' models based on pattern correlation, RMSE and bias are highlighted in blue. Results for individual seasons are shown in Tables D.3 (DJF) and D.4 (MAM).

MODEL	CORREL	RMSE mm/day	MEAN DIFF mm/day	NUM PTS
BMRCTR	.741	1.918	-.276	2592
CCC1TR	.735	1.720	-.120	2592
CCSRTR	.769	1.584	**.083**	2592
CERFTR	.792	1.586	-.402	2592
CSI2TR	.850	**1.324**	-.127	2592
CSM_TR	.786	1.880	-.432	2592
ECH3TR	.794	1.612	**-.105**	2592
ECH4TR	**.885**	**1.307**	-.138	2592
GFDLTR	.786	1.575	**.069**	2592
GISSTR	.708	1.901	-.496	2592
HAD2TR	**.892**	**1.268**	-.403	2592
HAD3TR	**.878**	1.394	-.243	2592
IAP_TR	.698	1.847	.430	2592
LMD_TR	.620	2.287	-.181	2448
MRI_TR	.697	1.913	-.224	2592
PCM_TR	.706	2.201	-.448	2592
MODBAR	.917	1.023	-.188	2592

TABLE D.3: **16 models : Variable = PRECIP : Season = DJF.** Model validation: comparing model baseline with observed data. Area specified by mask. Maskfile = MASK.A : Maskname = GLOBE. Cosine weighted statistics.

MODEL	CORREL	RMSE mm/day	MEAN DIFF mm/day	NUM PTS
BMRCTR	.684	1.834	-.374	2592
CCC1TR	.715	1.519	-.134	2592
CCSRTR	.726	1.480	**-.003**	2592
CERFTR	.657	1.706	-.398	2592
CSI2TR	.813	**1.244**	-.122	2592
CSM_TR	.603	2.131	-.377	2592
ECH3TR	.752	1.477	**-.078**	2592
ECH4TR	**.852**	**1.211**	-.162	2592
GFDLTR	.696	1.539	**.004**	2592
GISSTR	.649	1.847	-.440	2592
HAD2TR	**.842**	**1.295**	-.394	2592
HAD3TR	**.821**	1.413	-.262	2592
IAP_TR	.589	1.876	.444	2592
LMD_TR	.655	1.806	-.203	2448
MRI_TR	.621	1.844	-.282	2592
PCM_TR	.494	2.326	-.356	2592
MODBAR	.872	1.078	-.196	2592

TABLE D.4: **16 models : Variable = PRECIP : Season = MAM.** Model validation: comparing model baseline with observed data. Area specified by mask. Maskfile = MASK.A : Maskname = GLOBE. Cosine weighted statistics.

The above results are for the whole globe. They are of primary importance since they are a measure of overall model skill. It is important also to compare results over a specific study region, but one must be wary of results over limited areas. For example, if a model performed well over a small area, but badly over the globe, then the small-area result might simply be a fluke, a chance result. The smaller the study area, the more likely this is to happen. Thus, in carrying out a regional validation, a judicious choice must be made for the size of the area. The map below (Figure D.8) shows the region used for the present analysis (25 deg latitude by 25 deg longitude).

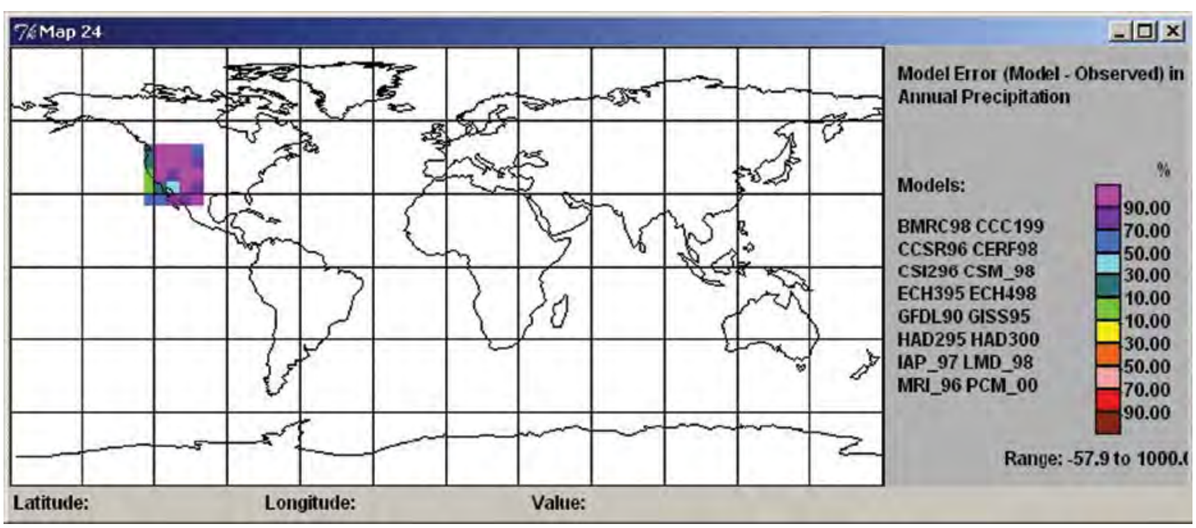


FIGURE D.8: **Same as Figure D.2, showing the regional study area.**

Pattern statistics for this region (from VALIDN.OUT) are shown in Tables D.5 (annual), D.6 (DJF) and D.7 (MAM). As before, the best three results are highlighted in blue.

MODEL	CORREL	RMSE mm/day	MEAN DIFF mm/day	NUM PTS
BMRCTR	**.766**	.817	**-.184**	25
CCC1TR	.667	1.288	-.857	25
CCSRTR	.515	.763	-.424	25
CERFTR	.715	1.464	-1.319	25
CSI2TR	.733	.910	-.665	25
CSM_TR	.579	1.075	-.885	25
ECH3TR	.688	**.565**	**-.157**	25
ECH4TR	.703	**.725**	-.519	25
GFDLTR	.517	1.608	-1.452	25
GISSTR	.698	1.350	-1.125	25
HAD2TR	**.791**	.813	-.576	25
HAD3TR	**.836**	.771	-.657	25
IAP_TR	.704	**.603**	**-.327**	25
LMD_TR	.604	1.431	-1.181	25
MRI_TR	.552	.803	-.498	25
PCM_TR	.554	1.243	-1.086	25
MODBAR	.766	.886	-.745	25

TABLE D.5: **16 models : Variable = PRECIP : Season = ANN.** Model validation: comparing model baseline with observed data. Grid box central points (5deg by 5deg grid). Latitude range = 27.5 to 47.5 DegreesN inclusive. Longitude range = -122.5 to-102.5 DegreesE inclusive. Latitude grid range 9,13 : longitude grid range 12,16 inclusive. Cosine weighted statistics.

MODEL	CORREL	RMSE mm/day	MEAN DIFF mm/day	NUM PTS
BMRCTR	.799	1.655	-.886	25
CCC1TR	.649	1.537	-.840	25
CCSRTR	.594	1.241	-.888	25
CERFTR	.764	2.028	-1.688	25
CSI2TR	.733	**1.058**	**-.663**	25
CSM_TR	.613	1.328	-.926	25
ECH3TR	.611	**1.033**	**-.366**	25
ECH4TR	**.855**	**.772**	**-.502**	25
GFDLTR	.484	2.231	-1.942	25
GISSTR	.667	1.497	-1.167	25
HAD2TR	**.817**	1.348	-.906	25
HAD3TR	**.821**	1.412	-1.037	25
IAP_TR	.686	1.524	-.994	25
LMD_TR	.772	2.051	-1.644	25
MRI_TR	.440	1.628	-1.071	25
PCM_TR	.754	1.212	-.938	25
MODBAR	.788	1.282	-1.029	25

TABLE D.6: **16 models : Variable = PRECIP : Season = DJF.** Model validation: comparing model baseline with observed data. Grid box central points (5deg by 5deg grid). Latitude range = 27.5 to 47.5 DegreesN inclusive. Longitude range = -122.5 to-102.5 DegreesE inclusive. Latitude grid range 9,13 : longitude grid range 12,16 inclusive. Cosine weighted statistics.

MODEL	CORREL	RMSE mm/day	MEAN DIFF mm/day	NUM PTS
BMRCTR	.856	.936	**-.503**	25
CCC1TR	.810	1.123	-.752	25
CCSRTR	.718	1.121	-.785	25
CERFTR	.802	1.628	-1.372	25
CSI2TR	.817	.877	-.706	25
CSM_TR	.716	1.128	-.932	25
ECH3TR	**.822**	**.586**	**-.221**	25
ECH4TR	.766	**.774**	-.632	25
GFDLTR	.578	1.681	-1.534	25
GISSTR	.763	1.602	-1.314	25
HAD2TR	**.837**	.954	-.737	25
HAD3TR	**.859**	.906	-.719	25
IAP_TR	.750	**.563**	**-.194**	25
LMD_TR	.743	1.625	-1.415	25
MRI_TR	.638	.962	-.546	25
PCM_TR	.778	1.040	-.857	25
MODBAR	.843	.981	-.826	25

TABLE D.7: **16 models : Variable = PRECIP : Season = MAM.** Model validation: comparing model baseline with observed data. Grid box central points (5deg by 5deg grid). Latitude range = 27.5 to 47.5 DegreesN inclusive. Longitude range = -122.5 to-102.5 DegreesE inclusive. Latitude grid range 9,13 : longitude grid range 12,16 inclusive. Cosine weighted statistics.

MODEL	CORREL	RMSE mm/day	MEAN DIFF mm/day	NUM PTS
BMRCTR	**.861**	**1.357**	.869	42
CCC1TR	.157	2.611	-.657	42
CCSRTR	.477	2.278	1.197	42
CERFTR	.678	1.537	.230	42
CSI2TR	.357	1.867	**.100**	42
CSM_TR	.695	1.518	.542	42
ECH3TR	.710	1.826	-.377	42
ECH4TR	.611	1.680	-.293	42
GFDLTR	-.172	2.501	.507	42
GISSTR	.477	1.780	.310	42
HAD2TR	**.875**	**.966**	**-.151**	42
HAD3TR	**.846**	**1.082**	**.121**	42
IAP_TR	.530	2.411	.436	42
LMD_TR	.212	2.187	.495	42
MRI_TR	.429	1.951	.529	42
PCM_TR	.553	1.865	.825	42
MODBAR	.787	1.317	.293	42

TABLE D.8: **16 models : Variable = PRECIP : Season = MAM.** Model validation: comparing model baseline with observed data. Grid box central points (5deg by 5deg grid). Latitude range = 7.5 to 37.5 DegreesN inclusive. Longitude range = -102.5 to -77.5 DegreesE inclusive. Latitude grid range 11,17 : longitude grid range 16,21 inclusive. Cosine weighted statistics.

Conclusion

The conclusion that may be drawn from these (limited) results is that the best five models are the two UK Hadley Centre models (HadCM2 and HadCM3), the two Max Planck Institute models from Germany (ECHAM3 and ECHAM4) and the Australian CSIRO Mk. 2 model. What is remarkable is that these models are arguably the best not only globally and for annual data, but also regionally and seasonally.

To expand on this point, my other (unpublished) analyses (with Ben Santer, PCMDI/LLNL) has shown that these models frequently outperform other models for most regions of the globe. Another example is given below, for a region covering the southeastern US and Central America.

For this region, there is no overall model-average bias in precipitation (annual results are shown in Figure D.9, which shows a window of Figure D.2 for this second study region).

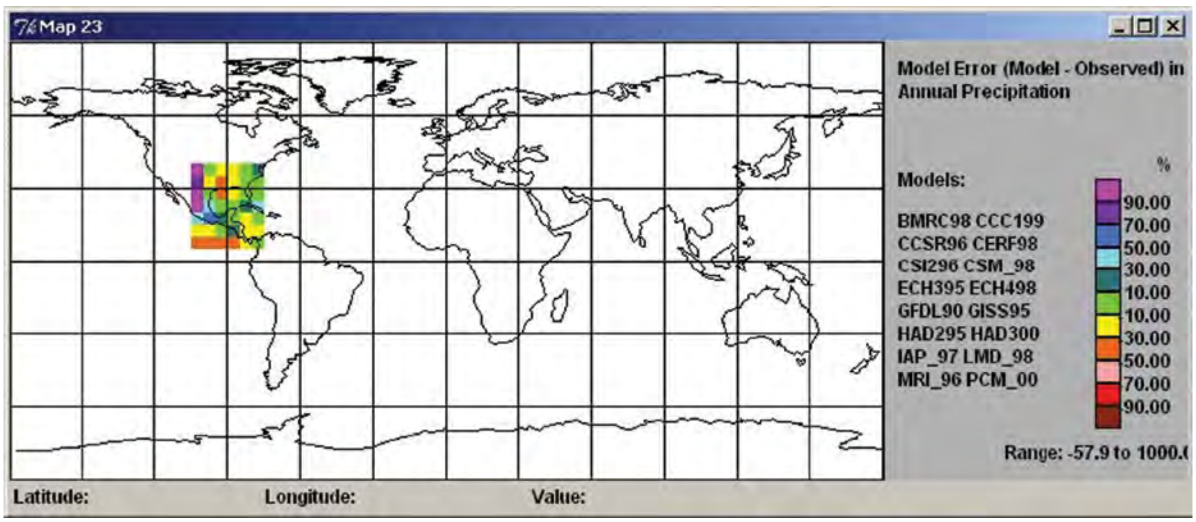


FIGURE D.9: **Annual mean precipitation errors over the second study region, averaged over 16 models.**

Regional comparison statistics are shown in Table D.8. The two Hadley Centre models are again the best performers. The MPI models are less good over this region, but still in top half of the group.

FIVE SELECTED GCM SIMULATIONS OF CURRENT CLIMATE

Figures E.1 and E.2 display observed temperature and precipitation for the two grid boxes in the central Rockies and the simulations of current climate in the five models. All data are from MAGICC/SCENGEN. Note that the seasonality of precipitation is quite different from precipitation patterns in Aspen (which peak in the fall and spring). This reflects an average of a grid box going as far north as Montana. All five models closely simulate the seasonality of observed temperatures, although model errors of as much as 5°C (9°F) in individual months are not uncommon.

For precipitation, the models' performance is more mixed. Three of the models (HadCM2, HadCM3, and ECH4) closely simulate the seasonality and magnitude of observed precipitation. CSIRO and ECHAM3 estimate too much precipitation, although their simulation of the seasonal pattern is roughly correct.

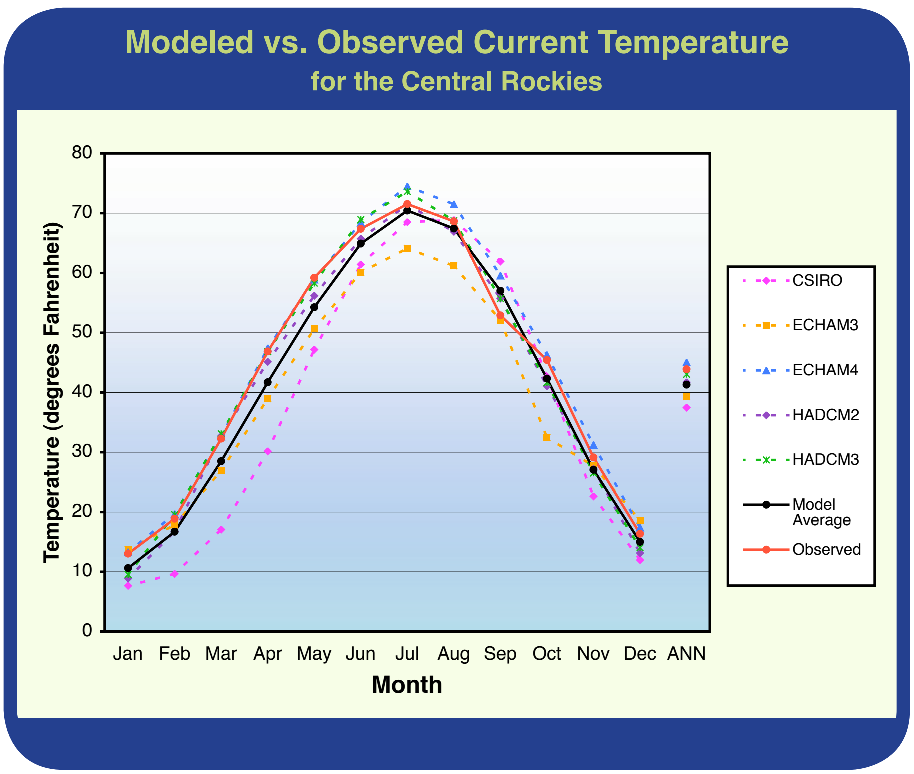


FIGURE E.1: **Model simulation of current temperature compared to actual observed temperature for the 5° x 10° grid box containing Aspen.** Current temperature is defined as the average for the period from 1961 to 1990.

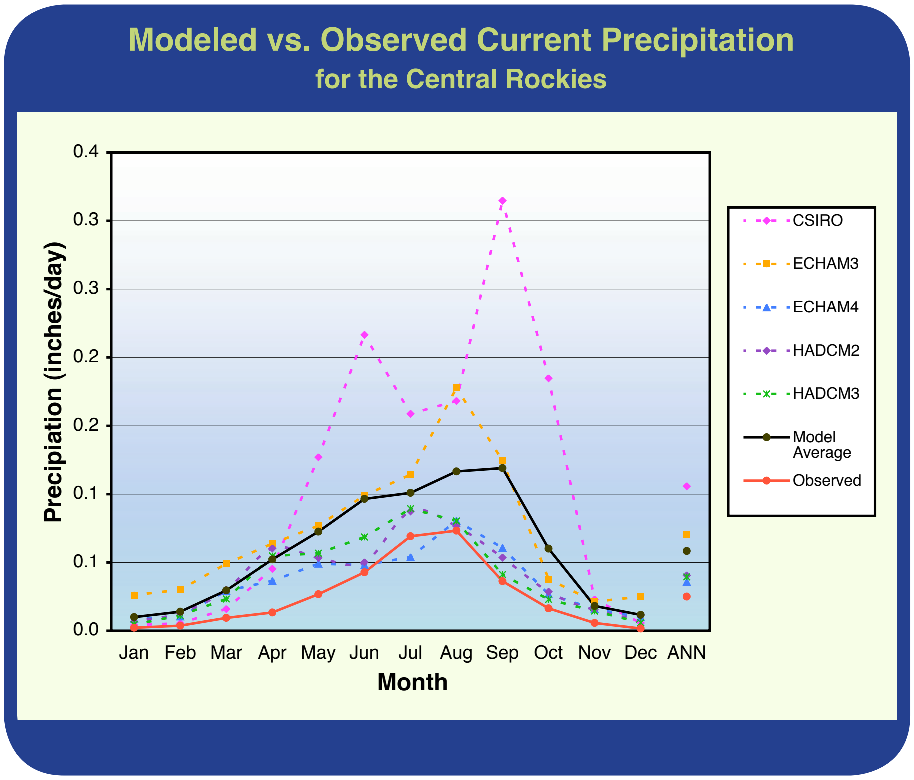


FIGURE E.2: **Model simulation of current precipitation compared to actual observed temperature for the 5° x 10° grid box containing Aspen. Current precipitation is defined as the average for the period from 1961 to 1990.**

GIS/REMOTE SENSING METHODS

Methods used to generate digital elevation model (DEM) and generate elevation classes

DEM data from the U.S. Geological Survey's (USGS's) National Elevation Dataset (NED) were downloaded from http://gisdata.usgs.net/ned/ for the USGS Hydrologic Unit (HUC) for the area that includes Aspen (USGS EROS Data Center, 1999). The DEM was processed using a GIS to generate a hydrologically correct DEM. The resultant elevation data were used to delineate a subwatershed for the point located at the confluence of Wood Creek and the Roaring Fork River. Then final DEM was subset to this watershed and classified into the following seven elevation zones:

7,200-8,300 (ft)	(2,195-2,530 [meters])
>8,300-9,300	(>2,530-2,835)
>9,300-10,300	(>2,835-3,139)
>10,300-11,300	(>3,139-3,444)
>11,300-12,300	(>3,444-3,749)
>12,300-13,300	(>3,749-4,054)
>13,300-14,300	(>4,054-4,359)

Total area and minimum, maximum, and mean elevation statistics were then generated for each elevation zone for use in the SRM model.

Methods used to generate landscape classes

Landscape classes, which are needed for the SNTHERM model, were generated within the GIS from a combination of Land Use/Land Cover (LULC), elevation, and aspect. Elevation and aspect classes were derived from the hydrologically correct DEM for the watershed. Elevation zones were grouped as follows (bold indicates the output class):

7,000 to 10,000 (ft) = **10,000**	(2134 to 3048 [meters])
10,000 to 12,000 = **12,000**	(3048 to 3658)
12,000 to 14,000+ = **14,000**	(3658 to 4267)

We split locations into north and south facing (i.e., > 90 to 270 is south). Finally, LULC data for the watershed were downloaded from the National Land Cover Data (NLCD) for 1992 (USGS, 2000). The LULC data were grouped into tree and non-tree classes using the following NLCD Land Cover Classification System attributes:

Non-Tree: water, developed, barren, shrubland, non-natural woody, herbaceous upland, and herbaceous planted/cultivated

Tree: forested upland (consisting of deciduous forest, evergreen forest, and mixed forest)

The three grouped data sets (LULC, aspect, and elevation) were then overlaid in the GIS into the landscape combinations in Table F.1.

Total area and minimum, maximum, and mean elevation statistics were then generated for each landscape class for use in the SNTHERM model.

Methods used to generate snow cover data

Snow cover was estimated using satellite data. Four Landsat 7, Enhanced Thematic Mapper (ETM+), level 1G, SLC-off gap filled scenes were acquired from USGS EROS Data Center (2001) covering the following dates: February, 3, 2001, April 9, 2001, May 11, 2001, and June 6, 2001. For the early season, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) L1B Registered Radiance at the Sensor imagery for September 30, 2000 and December 1, 2000 were obtained from the USGS, Land Processes Distributed Active Archive Center (LP DAAC) website (USGS LP DAAC, 2004). Unfortunately, unlike the Landsat scenes, the ASTER was only available for the eastern or western half of the watershed for any particular date. In addition, 2 scenes for each date (north and south) were required to cover the respective half of the watershed. Therefore, 2 scenes were used for each date.

Six Landsat bands (1-5, 7) and 2 ASTER bands (1 and 4), covering the visible to short wave infrared (SWIR) portion of the electromagnetic spectrum, were imported into ERDAS Imagine software (v.8.7) and combined into two respective multispectral images.[37] Each image was then orthorectified as follows. Numerous locations on the imagery were co-located with locations on an existing orthorectified summer (6/2002) Landsat mosaic image (USGS, 2004) and used as ground control points to georeference the unreferenced imagery to real-world locations. To correct for terrain displacement, the DEM was used as input into the orthorectification process. In processing the data, the nearest-neighbor method was used during resampling.

Landscape Combinations

Landscape class	Aspect	Forest	Elevation (ft)
1	South	Tree	10,000 - <12,000
2	North	Tree	10,000 - <12,000
3	South	Tree	7,000 - <10,000
4	South	No tree	7,000 - <10,000
5	North	No tree	7,000 - <10,000
6	North	Tree	7,000 - <10,000
7	South	No tree	10,000 - <12,000
8	South	No tree	10,000 - <12,000
9	North	No tree	12,000 - 14,000+
10	South	No tree	12,000 - 14,000+
11	North	Tree	12,000 - 14,000+
12	South	Tree	12,000 - 14,000+

TABLE F.1: **Landscape combinations.**

The ASTER orthorectified imagery was then mosaiced to generate two contiguous scenes as input to derive the snow covered area. The Normalized Difference Snow Index (NDSI), which exploits the high reflectance in wavelengths where snow is bright (green, 0.525-0.605 µm Landsat; 0.52-0.60 µm Aster) vs. wavelengths where snow is dark (SWIR, 1.55-1.75 µm Landsat; 1.60-1.70 µm Aster), was used to identify snow cover and was calculated as follows (Klein et al., 1998; Dozier and Painter, 2004). Equation 1 shows the ratio used for Landsat (TM) data:

$$NDSI = (TM\ band2 - TM\ band\ 5) / (TM\ band2 + TM\ band5) \qquad (1)$$

And equation 2 for ASTER data:

$$NDSI = (ASTER\ band1 - ASTER\ band4) / (ASTER\ band1 + ASTER\ band4) \qquad (2)$$

37. Note that for ASTER data, the SWIR band (4) has a spatial resolution of 30 meters, while the green band (1) has a spatial resolution of 15 meters. After comparing outputs of resampling the band 1 to 30 meters vs. resampling band 4 to 15 meters, it was decided that the latter provided a more realistic results of snow cover.

As land cover influences the spectral reflectance of the snow (e.g., branches of barren deciduous trees will have a different reflectance from non-obscured areas), clear areas were differentiated from dense forest, mixed forest, and deciduous forest. In clear areas an NDSI ratio > 0.4 was used for Landsat data and > 0.8 for ASTER data to classify snow. For Landsat data, to prevent areas of very dense coniferous forest from being falsely classified as snow, a mask was generated using reflectances of less than 11% in Landsat band 2. In deciduous and mixed forest areas, an NDSI ratio between 0.1 and 0.4 was used. These forest types were identified using the 1992 LULC dataset. Lastly, areas of clouds were masked from the analysis for both Landsat and ASTER data sets.

Once the snow covered area was identified, it was overlaid with the 7-classed elevation layer to calculate the percent snow cover by elevation class.

MEDIA

December 23, 1976 The Aspen Times Page 13-A

Business dislikes "disaster" status

Talent like US Senator Floyd Haskell's is needed in international circles like Outer Mongolia, suggested an Aspen Skiing Corporation official at the Tuesday noon meeting of the Aspen Chamber of Commerce.

From the warm reception that idea received, it would appear that being declared a "disaster area" has not pleased Aspen's business community.

The corporation's marketing director, George Madsen, said he was serious in his suggestion that Christmas greetings be sent to Senator Haskell complimenting him on "accurately predicting that Colorado would become a disaster area even before it was."

He was implying that the no-snow "disaster" publicity had itself discouraged tourists from visiting Aspen and other Western Slope ski resorts, thus creating the real disaster.

"I've seen enough politicians trying to get personal publicity at our expense, and I'm getting sick of it," asserted Madsen. "It would be nice if they talked to Colorado businesses and ski areas first."

In a voice vote called by Chamber President Ernestine Ashley, board members unanimously voted to forward Haskell the greetings and message.

When asked to write the letter, Madsen declined explaining that he might be "too vindictive." Realtor Wendy Morse's offer to compose the message was not readily accepted by the membership present, and it was unclear at the meeting who was going to write it.

Employee Incentive Delayed

Because many of Aspen's employees are not yet employed, the Chamber-sponsored "Employee Incentive Program" will be postponed until snow falls, but it would not be dropped, said President Ashley during the meeting.

She told the board that Thursday's meeting with employers had been attended by about 40, and that feedback on the program had been basically positive even though everyone realizes that giving three model employees prizes every week is not going to be a complete solution to the serious problem of Aspen's increasingly bad press.

Since that meeting, some have called in commitments to give what Ashley characterizes as "meaningful prizes."

Prizes Donated to Date

Prizes, she told the **Aspen Times**, include a $150 season memberhip to the Aspen Meadows Health Spa, three separate $70 gift certificates at Aspen Stereo, weekly $10 gift certificates at Aspen Safari, $10 weekly gift certificates at the Magic Pan, weekly refunds on Host Ski Passes by the Aspen Skiing Corporation, a ski pass from Trost & Wright Western Fashions, dinner and wine for two at the Copper Kettle donated by Cooley Investment Co, $100 in cash from Ashley Moore, an electric coffee grinder and coffee from the Aspen Tea and Spice Company, and $100 in cash from the **Aspen Times**.

Ashley said she found the commitments encouraging, and expects more to follow as the program gets underway.

Tri-City Meeting

In other business, Executive Director Geraldine Fox announced that a United Airlines official would speak on "marketing our areas" at a Jan 13 meeting in Carbondale of the Carbondale, Basalt, and Aspen Chambers.

Chamber members can bring spouses and friends, she said. The event is tentatively scheduled at the Stagecoach beginning with cocktails at 6:30 pm, she said.

The last such meeting among the three chambers was in Aspen this past May.

Recovery Party

"We can do without snow," declared county employee Brian Stafford in announcing yesterday's "Great Aspen Recovery Party" which he, City Council member Nina Johnston and County Commissioner-elect Bob Childs planned.

Activities included music in the mall, a three-legged uphill slalom, a tug of war, and snow dance.

Chamber Director Fox said that her office had developed a list of suggested "no snow" activities that is being distributed "so the people who did come will have a better experience."

Transportation Meeting

After President Ashley brought the board up to date on the Citizens' Advisory Transportation Committee, it was decided that a town meeting will be called in late January or early February on transportation alternatives.

Ashley represents the business community on the advisory committee.

—Adele Dusenbury

106—Rocky Mountain News Sat, Dec 18, 1976, Denver, Colo

Lack of snow is turning Aspen into disaster area

By MIKE MADIGAN
News Staff

ASPEN — There is no joy in Snowville

There also is no snow, no skiers, no tourists, no business, no money and — with no blizzards bearing down on Colorado mountains — little chance this major recreation area will open by Monday, Dec. 20, the latest opening date (in 1962) in modern time

"The Great White Hope" is not a boxer. It's a small storm forecast to move in over the weekend which maybe could provide the three inches of snow Aspen Skiing Corporation says it would need to open the western half of Buttermilk, one of the four resorts here

Until then, at least, the upper lifts of Highlands are the only ones operating. And seven inches of snow there, even with artificial snow-making equipment, won't last long in recent high temperatures

Aspen without snow in the winter is like Hawaii without the Pacific Ocean.

The town is hurting

MEETING AN UNEMPLOYED bar maid or lift operator on the street, about the worst thing a well-meaning visitor could say is "Beautiful warm weather isn't it?"

Aspen Ski Corp., which this time of the year usually employes close to 700 people, has only about 100 on its present payroll. And George Madsen, vice president of marketing, estimates the Ski Corp.'s four resorts — Aspen Mountain, Buttermilk and Snowmass here and Breckenridge — are losing approximately $100,000 a d[illegible] ticket revenu[illegible] crowds [illegible]

week's World Pro Skiing events, half of which were originally scheduled to be run on Little Nell's porch, were going to be a gift. But then we lost that because there's no snow."

The pro races are all being held at Highlands now. The food concessionaire there, George Gordon, would like to thank somebody

"The crowds are about half of what they were last year for the races," said Gordon. "But being the only place in town that's open, and being the only ski-area restaurant that's open, I'm very happy to be here."

Of motel's 20 units only four occupied most of the week

The ski and sports may be hit the hardest, and Pancho's Ski Repair Shop is one of the smallest

"Last year at this time I was doing about $1,500 a week business. But I'm not doing anything this year, probably not for six weeks," said owner Phil Potvin

"For instance, last year was a big year so everybody ordered 10 to 20 per cent more ski bindings this year. I've sold a lot of used bindings this year, but I haven't sold a new pair yet."

IF POTVIN THOUGHT of his store as being small before, when he paid seven employes, imag[illegible] [illegible]ating it by him[illegible]

Disaster publicity or pre-publicity?

December 16, 1976 The Aspen Times Page 9-D

Lack of snow hurts Aspen business

The 1976 year of no snow has already caused about a $1 million loss of revenue to the Aspen Skiing Corp.

It has caused more Aspenites than ever to line up at the unemployment office in Glenwod Springs.

It is causing Aspen lodges to offer special discounts in hopes that skiers will come...if only to enjoy an old-fashioned Christmas in an old silver mining town...and do some cross-country skiing.

Aspen Skiing Corp

There hasn't been enough snow for the Aspen Skiing Corp to begin running the lifts.

Tom Richardson, vice president and general manager of the Aspen Skiing Corp, which operates Aspen Mountain, Buttermilk, Snowmass and Breckenridge, said the company had revenues last year for the period to Dec 17 of $641,000 in lift tickets at Aspen and $355,000 in lift tickets at Breckenridge. Revenue from the Aspen Ski School was $90,000, he said, and revenue from the Breckenridge Ski School was $26,000.

The sign man is back for the winter, and Aspen residents are doing some shopping, but tourists are few and far between this Christmas season. Adele Dusenbury photo.

He said that at this time of year, the Ski Corp would normally have 900 employees and this year there are only about 100 people on the payroll.

"The whole hotel and restaurant business depends upon having skiing in the area," Richardson said. "Of course, some people still come, but the lack of snow has reduced the number of people for the restaurants and hotels considerably."

Officials at the Ski Corp estimate that six to eight inches of snow would be enough to open the ski runs and lifts. "We can start two days after it storms," said Richardson.

Job Service To Open

Jack Dalton, manager of the Job Service and Unemployment Office in Glenwood Springs said that a higher number of Aspenites than usual, about 200 compared to about 50 a week for this time of year, have been applying for unemployment compensation.

"These are not transients," he said. "These are residents who normally go to work for the ski areas or restaurants and lodges by Thanksgiving.

"We had one woman come in Tuesday, who said she had worked six years for the same restaurant, and was laid off for the first time."

To try to help matters, the Colorado Department of Employment will open a temporary job Service Office on Monday, Dec 20, in Aspen. The office will be open from 8 am to 5 pm in space provided by the City of Aspen...sharing the office of the dog catcher, in the Wheeler Opera House.

The office will be run by Pat Hart the first week and then by Judy Dysart.

"Once the snow hits the ground, we expect to have a lot of jobs," explained Dalton, "and we want to place people as soon as possible and musicians."

Peter Ashworth, who is director of Aspen Reservations, Inc, the joint reservation ageency for the Aspen Ski Corp and Highlands Ski Corp and spokesman for the lodge industry said, "Many lodges have gone to summer rates for Christmas. The basic refund policy, being adopted by most of the lodge owners is to refund 100% through Dec 18. From then on, it is up to each lodgeowner to contact his guests and literally negotiate. Some lodges are explaining that they will give reduced rates until it snows, and then will make an adjustment. Others are offering to shift the reservation to another period.

"The lodges are being optimis- until after the first of the year when the billing from suppliers usually hits the ski industry. If it snows soon, we don't expect any large increase in applications for loans."

Statewide

The lack of snow has not only hurt Aspen, it is a matter of statewide concern in this Switzerland of America.

R Garrett Mitchell, president of Colorado Ski Country, USA, the Denver-based industry organization, confirmed that lack of snow has adversely affected the industry so far.

"People from all over are checking with us on a daily basis to find out if there's any skiing," Mitchell said.

When the ski industry misses a Thanksgiving, he said, "they don't get penalized—a good Thanksgiving is a bonus—but if they miss the two-week Christmas-New Year season, then you would start to see a negative effect on ski operators, resorts, hotels, restaurants and so forth."

During last year's Christmas-New Year's holiday, he said, the industry had 1,009,158 "skier days" during the 16-day holiday period.

Another industry source estimated that holiday skiers spent about $50 per day—including lodgings, meals, and other expenses, giving the overall Christmas ski holiday a value of at least $50 million.

Mitchell refuses to take a totally pessimistic view about a poor Christmas. Loss of most of the Christmas season, he says, wouldn't constitute a disaster. But if poor conditions continued into the latter part of January, "then I'm afraid you're in a very

LIST OF ACRONYMS AND ABBREVIATIONS

A1	Emissions scenario. *See Appendix A*
A1B	Emissions scenario. *See Appendix A*
A1FI	Emissions scenario. *See Appendix A*
A2	Emissions scenario. *See Appendix A*
af	acre feet
ASC	Aspen Skiing Company
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
B1	Emissions scenario. *See Appendix A*
cfs	cubic feet per second
COGAP	Colorado Gap Analysis Project
CSIRO	Australian Commonwealth Scientific and Industrial Research Organization
CWCB	Colorado Water Conservation Board
DEM	digital elevation model
ECHAM3	Climate model developed by the Max Planck Institute for Meteorology, Germany (version 3)
ECHAM4	Climate model developed by the Max Planck Institute for Meteorology, Germany (version 4)
ETM+	Enhanced Thematic Mapper Plus, an instrument carried on the Landsat 7 Satellite
GCM	General Circulation Model
GDP	Gross Domestic Product
GHG	Greenhouse gas
GIS	Geological Information Systems
GMT	Global mean temperature
gpd	gallons per day
GtC	gigatons of carbon
HadCM2	Climate Model developed at Hadley Model, United Kingdom Meteorological Office (version 2)
HadCM3	Climate Model developed at Hadley Model, United Kingdom Meteorological Office (version 3)
HRV	Historic range of variability
HUC	USGS Hydrologic Unit
IPCC	Intergovernmental Panel on Climate Change
LP DAAC	Land Processes Distributed Active Archive Center
LULC	Land Use/Land Cover
MAGICC	Model for the Assessment of Greenhouse-gas Induced Climate Change
MC1	A dynamic general vegetation model
MODIS	Moderate Resolution Imaging Spectroradiometer
NCAR	National Center for Atmospheric Research
NDSI	Normalized Difference Snow Index
NED	USGS National Elevation Dataset
PCM	parallel climate model

LIST OF ACRONYMS AND ABBREVIATIONS

PCMDI	Progrm for Climate Model Diagnosis and Intercomparison
PDF	probability distribution function
RCM	regional climate model
RMNP	Rocky Mountain National Park
SCA	snow covered area
SCENGEN	a global and regional SCENario GENerator
SDSM	statistical downscaling model
SNOTEL	SNOwpack TELemetry
SNTHERM	a physically based snow model
SRES	IPCC Special Report on Emissions Scenarios
SRM	snowmelt runoff model
SWE	snow water equivalent
TAR	IPCC Third Assessment Report
Tmax	maximum temperature
Tmin	minimum temperature
URF	Upper Roaring Fork
USDA	United States Department of Agriculture
USGS	United States Geological Survey
VINCERA	Vulnerability & Impacts of North American Forests to Climate: Ecosystem Responses & Adaptation

Adams, R.M., B.H. Hurd, and J. Reilly. 1999. A Review of Impacts to U.S. Agricultural Resources. Prepared for the Pew Center on Global Climate Change, Arlington, VA. February. http://www.pewclimate.org/docUploads/env%5Fargiculture%2Epdf. Accessed June 15, 2006.

Allen, R. B., R. K. Peet, and W. L. Baker. 1991. Gradient of analysis of latitudinal variation in southern Rocky Mountain forests. *Journal of Biogeography* 18:123-139.

Anderson, C.R. 2005. Modeling Spatially-Distributed Snowpack Properties to Enhance our Understanding of Snow-Elk Relationships in the Northern Elk Winter Range, Yellowstone National Park. Masters Thesis. University of Colorado-Boulder, Boulder, CO.

Anderson, Paul. 2004. Power In the Mountains: The History of The Aspen Municipal Electric Utility. Published by the City of Aspen.

Andronova, N.E. and M.E. Schlesinger. 2001. Objective estimation of the probability distribution for climate sensitivity. *Journal of Geophysical Research* 106:22,605-22,612.

Aspen Chamber of Commerce and Resort Association. 2006. http://www.aspenchamber.org/.

Aspen Skiing Company. 2003-2004 Sustainability Report. http://www.aspensnowmass.com/environment/programs/2004_ASC_Sustainability_Report.pdf. Accessed March 15, 2006.

Bachelet, D., J. M. Lenihan, C. Daly, R. P. Neilson, D. S. Ojima, and W. J. Parton. 2001. MC1: A dynamic vegetation model for estimating the distribution of vegetation and associated carbon, nutrients, and water technical documentation. Version 1.0. Gen. Tech. Rep. PNW-GTR-508. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR. 95 pp.

Bachelet, D., R.P. Neilson, J.M. Lenihan, and R.J. Drapek. 2001. Climate change effects on vegetation distribution and carbon budget in the United States. *Ecosystems* 4:164-185. See also http://216.48.37.142/pubs/2923.

Beever, E. A., P. F. Brussard, and J. Berger. 2003. Patterns of apparent exptirpations among ilsolated populations of pikas. *Journal of Mammology* 84:37-54.

Benayas, J. M. R., S. M. Scheiner, M. G. Sánchez-Colomer, and C. Levassor. 1999. Commonness and rarity: theory and application of a new model to Mediterranean montane grasslands. *Conservation Ecology* [online] 3:5. Available online at: http://www.consecol.org/vol3/iss1/art5/.

Best, Allen. 2001. "Ski area arms race dirties water." *High Country News*. January 29. http://hcn.org/servlets/hcn.Article?article_id=10229. Accessed March 15, 2006.

Bormann, F. H., and G. E. Likens 1979. Pattern and Process in a Forested Ecosystem : Disturbance, Development, and the Steady State Based on the Hubbard Brook Ecosystem Study. Springer-Verlag, New York.

Borys, R.D., D.H. Lowenthal, S.A. Cohn, and W.O.J. Brown. 2003. Mountaintop and radar measurements of anthropogenic aerosol effects on snow growth and snowfall rates. *Journal of Geophysical Research Letters* 30(10):1538.

BRW, Dames & Moore, and Colorado State University. 1999. Roaring Fork and Frying Pan Rivers Multi-Objective Planning Project. Prepared for the Colorado Water Conservation Board by BRW, Inc. June.

Burki, R., Elsasser, H., Abegg, Bruno. 2003. Climate Change and Winter Sports: Environmental and Economic Threats. 5th World Conference on Sport and Environment, Turin, December 2-3, 2003. http://www.unep.org/home/documents/Burki_report.doc. Accessed March 1, 2006.

REFERENCES

CCSP (Climate Change Science Program). 2006. *Temperature Trends in the Lower Atmosphere: Steps for Understanding and Reconciling Differences.* Thomas R. Karl, Susan J. Hassol, Christopher D. Miller, and William L. Murray (eds). A Report by the Climate Change Science Program and the Subcommittee on Global Change Research, Washington, DC.

CDOW. 1998. Colorado Gap Analysis Land Cover Data. Available online at http://ndis.nrel.colostate.edu/ftp/gap/index.html. Colorado Gap Analysis Project, Colorado Division of Wildlife, Denver, CO.

Center of the American West, University of Colorado at Boulder. 1997. *Atlas of the New West: Portrait of a Changing Region*. W. Riebsame, J. Robb, and D. Theobald (eds). W. W. Norton & Co., New York.

City of Aspen. 2000. Aspen Area Community Plan. February. http://www.aspenpitkin.com/pdfs/depts/7/aacp.pdf. Accessed March 2, 2006.

City of Aspen and Pitkin County, 2006. http://www.aspenpitkin.com/.

City of Aspen Water Department. 2005a. Aspen Colorado Precipitation Data. Available: http://www.aspenpitkin.com/pdfs/depts/58/prcpsumm.pdf. Accessed May 18, 2005.

City of Aspen Water Department. 2005b. Aspen Colorado Snowfall Data. Available: http://www.aspenpitkin.com/pdfs/depts/58/snowsumm.pdf. Accessed May 18, 2005.

Clarke, Sharon. 2006. Stream Flow Survey Report. Prepared for the Roaring Fork Conservancy. http://www.roaringfork.org/images/publications/Stream_Flow_Survey_Project_Report_January_2006_FINAL.pdf. Accessed March 23, 2006.

Colorado Division of Forestry. 2004. Report on the Health of Colorado's Forests – 2004. Colorado Department of Natural Resources – Division of Forestry. Denver, Colorado.

Colorado Judicial Branch, Water Clerk. 2000. Resume of the applications and amended applications filed with the water clerk for Water Division 5 during the Month of October 2000. http://www.courts.state.co.us/supct/watercourts/wat-div5/2000resumes/oct2000.pdf.

Colorado River Outfitters Association. 2003. Commercial River Use in Colorado: Executive Summary. http://www.croa.org/pdf/2003-commercial-rafting-use-report.pdf. Accessed February, 21, 2006.

Colorado Water Conservation Board (CWCB; http://cdss.state.co.us/ftp/statemod.asp)

Colorado Water Resources Research Institute and Colorado Water Conservation Board. 2002. Colorado Drought Conference: Managing Water Supply and Demand in Time of Drought. CWRRI Information Series Report No. 96. December 3, 2002. http://cwrri.colostate.edu/pubs/series/information/drought.pdf.

Condon, Scott. "What's in store for our water?" *The Aspen Times*. May 8, 2005. http://www.basaltchamber.com/sitepages/pid175.php. Accessed January 26, 2006.

Condon, Scott. "Roaring Fork River Finds Relief From Dry Conditions." *The Aspen Times*. August 14, 2003. http://72.14.203.104/search?q=cache:JkfORq-eYmwJ:www.aspentimes.com/apps/pbcs.dll/article%3FAID%3D/20030814/NEWS/308130032%26template%3Dprintart+Condon,+Scott.+%E2%80%9CRoaring+Fork+River+Finds+Relief+From+Dry+Conditions.%E2%80%9D&hl=en&gl=us&ct=clnk&cd=2. Accessed February 21, 2006.

Crandall, K. 2002. Fryingpan Valley Economic Study. Prepared for the Roaring Fork Conservancy, Basalt, Colorado.

Dai, A., W.M. Washington, G.A. Meehl, T.W. Bettge, and W.G. Strand. 2004. The ACPI climate change simulations. *Climatic Change* 62(1-3):29-43.

Davies, D., Watson, P., and Thilmany, D. 2004. Resource and Environmental Aspects of Golf in Colorado. *Agriculture and Resource Policy Report*. Department of Agricultural and Resource Economics, Fort Collins, CO. April Issue. http://dare.agsci.colostate.edu/csuagecon/extension/docs/impactanalysis/apr04-01.pdf. Accessed March 27, 2006.

Dettinger, M.D., D.R. Cayan, M.K. Meyer, and A.E. Jeton. 2004. Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River Basins, Sierra Nevada, California, 1900-2099. *Climatic Change* 62:283-317.

District Court Water Division NO. 1. 1987. Stipulation in the Application for Water rights of South Adams County Water and Sanitation District. Case Number W-8440-76D.

Dozier, J. and T. Painter. 2004. Multispectral and hyperspectral remote sensing of alpine snow properties. *Annual Review of Earth Planet Science* 32:465-494.

Dunn, P. O., and D. W. Winkler. 1999. Climate change has affected the breeding date of Tree Swallows throughout North America. *Proceedings of the Royal Society of London, Series B* 266:2487-2490.

Futuyuma, D. J., and G. Moreno. 1988. The evolution of ecological specialization. *Annual Review of Ecology and Systematics* 19:207-233.

Elsasser, H. and R. Burki. 2002. Climate change as a threat to tourism in the Alps. *Climate Research* 20(3):253-257.

Enartech, Inc. 1997. City of Aspen: Implications of Groundwater Withdrawals on Local Stream Flow Conditions. Prepared for City of Aspen Department of Utilities. February.

Enartech, Inc. 1994. City of Aspen: Evaluation of Raw Water Availability. Prepared for City of Aspen Department of Utilities. October.

EPA. 1997. Climate Change and Colorodo. EPA 230-F-97-008f. U. S. Environmental Protection Agency.

Fitzgerald, J. P., C. A. Meaney, and D. M. Armstrong 1994. Mammals of Colorado. Denver Museum of Natural History; University Press of Colorado, Niwot, Colo.

Forest, C.E., P.H. Stone, A.P. Sokolov, M.R. Allen, and M.D. Webster. 2002. Quantifying uncertainties in climate system properties with the use of recent climate observations. *Science* 295:113-117.

Fox, L. R., and P. A. Morrow. 1981. Specialization: species property or local phenomenon? *Science* 211:887-893.

Gadgil, M. 1971. Dispersal: population consequences and evolution. *Ecology* 52:253-261.

Gleick, P.H. 1990. Vulnerability of water systems. In *Climate Change and U.S. Water Resources*, P.E. Waggoner (ed.). John Wiley & Sons, New York.

Hamilton, J.M., D.J. Maddison, and R.S.J. Tol. 2005. Effects of climate change on international tourism. *Climate Research* 29(3):245-254.

Hansen, E.M., B.J. Bentz, and D.L. Turner. 2001. Temperature-based model for predicting univoltine brood proportions in spruce beetle (Coleoptera: Scolytidae). *The Canadian Entomologist* 133:827-841.

Harrison, S. J., S. J. Winterbottom, and R. C. Johnson. 2001. A preliminary assessment of the socio-economic and environmental impacts of recent changes in winter snow cover in Scotland. *Scottish Geographical Journal* 117(4):297-312.

Harrison, S. J., S. J. Winterbottom, and C. Sheppard. 1999. The potential effects of climate change on the Scottish tourist industry. *Tourism Management* 20(2):203-211.

Hartman, Todd. 2004. "Aspen's Roaring Fork River could drop to a whisper." *Rocky Mountain News*. October 6, 2004. http://knight.stanford.edu/risser/winners/2005/lastdrop-p4.html. Accessed January 26, 2006.

REFERENCES

Haxeltine, A., and I. C. Prentice. 1996. BIOME3: An equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability and competition among plant functional types. *Global Biogeochemical Cycles* 10:693-710.

Hayhoe et al. 2004. Emissions pathways, climate change and impacts on California. *Proceedings of the National Academy of Sciences* 101:12422- 12427.

Heede, R. 2006. Aspen Greenhouse Gas Emissions 2004 for the City of Aspen's Canary Initiative. Climate Mitigation Services. Old Snowmass, Colorado.

Hempel, P. and K. Crandall. 2001. Roaring Fork Watershed Year 2000 State of the River Report. The Roaring Fork Conservancy. November. http://www.roaringfork.org. Accessed March 1, 2006.

Hersteinsson, P., and D. W. Macdonald. 1992. Interspecific competition and the geographical distribution of red and arctic foxes, Vulpes vulpes and Alopex lagopus. *Oikos* 64:505–515.

Hess, K., and R. R. Alexander 1986. Forest Vegetation of the Arapaho and Roosevelt National Forests in Central Colorado: a Habitat Type Classification. U.S. Dept. of Agriculture Forest Service Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO.

Hisschemoller, M., R. S. J. Tol, and P. Vellinga. 2001. The relevance of participatory approaches in integrated environmental assessment. *Integrated Assessment* 2:57-72.

Hobbs, N.T et al. 2004. Impacts of Climate Change on Rocky Mountain National Park and its Gateway Community. Natural Resource Ecology Lab, Colorado State University, Fort Collins. Available at http://www.nrel.colostate.edu/projects/star/.

Hobbs, N. T., J. S. Baron, S. Cooney, D. J. Cooper, J. E. Dickens, H. Galbraith, A. P. Covich, J. B. Loomis, E. Martinson, D. Ojima, R. D. Scherer, D. M. Theobald, G. Wang, and S. A. Weiler. 2003. Future Impacts of Global Climate on Rocky Mountain National Park: Its Ecosystems, Visitors, and the Economy of its Gateway Community – Estes Park. Available online at http://www.nrel.colostate.edu/projects/star/papers/2003_final_report.pdf. Colorado State University and Institute of Arctic Alpine Research, University of Colorado.

Hoffman, G. R., and R. R. Alexander 1983. Forest Vegetation of the White River National Forest in Western Colorado: a Habitat Type Classification. Rocky Mountain Forest and Range Experiment Station Forest Service U.S. Dept. of Agriculture, Fort Collins, CO.

Holsten, E.H., R.W. Their, A.S. Munson, and K.E. Gibson. 1999. Physiological basis for flexible voltinism in the spruce beetle (Coleoptera: Scolytidae). *The Canadian Entymologist* 133: 805-17.

Holten, J. I., and P. D. Carey 1992. Responses of Climate Change on Natural Terrestrial Ecosystems in Norway. Norwegian Institute for Nature Research, Trondheim.

Hoover, R. L., and D. L. Wills 1984. Managing Forested Lands for Wildlife. Colorado Division of Wildlife, Denver, CO. 459 pp.

Inouye, D. W., B. Barr, K. B. Armitage, and B. D. Inouye. 2000. Climate change is affecting altitudinal migrants and hibernating species. *Proceedings of the National Academy of Science* 97:1630-1633.

IPCC (Intergovernmental Panel on Climate Change). 2001a. *Climate Change 2001: The Scientific Basis.* Houghton, J.T., Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden, D. Xiaosu, and K. Maskell (eds.). Cambridge: Cambridge University Press.

IPCC. 2001b. *Climate Change 2001: Synthesis Report.* R.T. Watson and the Core Writing Team (eds.). Cambridge, U.K.: Cambridge University Press.

IPCC. 2000a. *Special Report on Emissions Scenarios***.** N. Nakicenovic and R. Swart (eds.). Cambridge University Press, UK.

IPCC. 1998. *The Regional Impacts of Climate Change: An Assessment of Vulnerability*. RT Watson, MC Zinyowera, RH Moss (eds). Cambridge University Press, Cambridge, UK. Available at: http://www.grida.no/climate/ipcc/regional/index.htm.

Jordan, R. 1991. A One-dimensional Temperature Model for a Snow Cover. Special Report 91-6. US Army Cold Regions Research and Engineering Laboratory, Hanover, NH.

Kerr, R.A. 2004. Three degrees of consensus. *Science* 305:932-934.

Kingery, H. E. 1998. Colorado breeding bird atlas. Colorado Bird Atlas Partnership : Colorado Division of Wildlife, Denver, Colo.

Klein, A.G., D.K. Hall, and K. Siedel. 1998. Algorithm intercomparison for accuracy assessment of the MODIS snow — mapping algorithm. *Proceedings of the 55th Annual Eastern Snow Conference*, Jackson, NH, June 2-3, 1998, pp. 37-45.

Krementz, D. G., and P. Handford. 1984. Does avian clutch size increase with altitude? *Oikos* 43:256-259.

Kutiel, P. 1992. Slope aspect effect on soil and vegetation in a Mediterranean ecosystem. *Israel Journal of Botany* 41:243–250.

Leatherman, D.A., D.S. Farmer, and D.S. Hill. 2005. Gypsy Moth. *Insect Series – Trees & Shrubs. no. 5.539.* Colorado State University Cooperative Extension. March.

Lenihan, J.M., R. Drapek, D. Bachelet, and R.P. Neilson. 2003. Climate change effects on vegetation distribution, carbon, and fire in California. *Ecological Applications* 13(6):1667-1681.

Leung, L.R. and Y. Qian. 2005. Hydrologic response to climate variability, climate change, and climate extreme in the U.S.: Climate model evaluation and projections. In *Regional Hydrological Impacts of Climatic Change – Impact Assessment and Decision Making,* Wagener, T. et al. (eds.). IAHS Publication 295, pp. 37-44.

Leung, L.R., Y. Qian, X. Bian, W.M. Washington, J. Han, and J.O. Roads. 2004. Mid-century ensemble regional climate change scenarios for the western United States. *Climatic Change*, 62(1-3):75-113.

Leung, L.R., Y. Qian, and X. Bian. 2003a. Hydroclimate of the western United States based on observations and regional climate simulation of 1981-2000. Part I: Seasonal statistics. *Journal of Climate* 16(12):1892-1911.

Leung, L.R., Y. Qian, X. Bian, and A. Hunt. 2003b. Hydroclimate of the western United States based on observations and regional climate simulation of 1981-2000. Part II: Mesoscale ENSO anomalies. *Journal of Climate* 16(12):1912-1928.

Leung, L.R., L. mearns, F. Giorgi, and R. Wilby. 2003c. Regional climate research: needs and opportunities. *BAMS* January 2003:89-95.

Li, S.-H. a. J. L. B. 1999. Influence of climate on reproductive success in Mexican Jays. *Auk* 116:924-936.

Logan, J.A. and J.A. Powell. In Press. Ecological consequences of climate change altered forest insect disturbance regimes. In *Climate Change in Western North America: Evidence and Environmental Effects*, F.H. Wagner (ed.). Allen Press, Lawrence, KS.

Logan, J.A. and J.A. Powell. 2001. Ghost forests, global warming, and the mountain pine beetle. *American Entomologist* 47:160-173.

Logan, J.A., J. Regniere, D.R. Gray, and A.S. Munson. In review. Risk assessment in the face of a changing environment: Gypsy moth and climate change in Utah. Submitted to *Ecological Applications*.

Lyon, P., J. Sovell, and J. Rocchio. 2001. Survey of Critical Biological Resources - Garfield County. Colorado Natural Heritage Program, Fort Collins, CO.

Martin, K., and K. L. Wiebe. 2004. Coping Mechanisms of Alpine and Arctic Breeding Birds: Extreme Weather and Limitations to Reproductive Resilience. *Integrative and Comparative Biology* 44:177-185.

REFERENCES

Martinec, J., A. Rango, and R. Roberts. 1994. *The Snowmelt Runoff Model (SRM) User's Manual,* M.F. Baumgartner (ed.). Geographica Bernensia, Department of Geography, University. of Berne, Switzerland.

Martinec, J. 1975. Snowmelt-runoff model for stream flow forecasts. *Nordic Hydrology* 6(3):145-154.

Mastrandrea, M.D. and S.H. Schneider, 2004. Probablistic integrated assessment of dangerous climate change. *Science* 304: 571-575.

McKenzie, D., Z. Gedalof, D. Peterson, and P. Mote. 2004. Climatic change, wildfire, and conservation. *Conservation Biology* 18:890-902.

McNeely, J. A. 1990. Climate Change and Biological Diversity Policy Implications. Pages 406-429 in M. M. Boer, and R. S. D. Groot, editors. Landscape-ecological Impact of Climatic Change, edited by , . IOS Press., Amsterdam.

Merriam, C. H. 1890. Results of a biological survey of the San Francisco Mountain region and desert of the Little Colorado, Arizona. Government Printing Office, Washington, D.C. 208 pp.

Miller, N.L., K.E. Bashford, and E. Strem. 2003. Potential impacts of climate change on California hydrology. *Journal of the American Water Resources Association* 39:771-784.

Morgan, P., G. H. Aplet, J. B. Haufler, H. C. Humphries, M. M. Moore, and W. D. Wilson. 1994. Historical range of variability: A useful tool for evaluating ecosystem change. *Journal of Sustainable Forestry* 2:87-111.

Murphy, D. D., and S. B. Weiss. 1992. Effects of Climate Change on Biological Diversity in Western North America: Species Losses and Mechanisms. Pages 355-368 in R. L. Peters, and T. E. Lovejoy, editors. Global warming and biological diversity. Yale University Press, New Haven.

National Assessment Synthesis Team (NAST). 2000. Climate Change Impacts on the United States: the Potential Consequences of Climate Variability and Change, U.S. Global Change Research Program, Washington, DC.

Neilson, R. P. 1995. A model for predicting continental-scale vegetation distribution and water balance. *Ecological Applications* 5:362-385.

Neilson, R. P. 1993. Transient ecotone response to climatic change: some conceptual and modelling approaches. *Ecological Applications* 3:385-395.

Neilson, R.P., D. Bachelet, J.M. Lenihan, and R.J. Drapek. 2005. Comparing new and old scenarios of future climate change impacts on fire, carbon, and vegetation dynamics in eastern U.S. forests. *EastFIRE Conference Proceedings – Published Abstracts.* May 11-13, George Mason University, Fairfax Campus, VA.

O'Keefe, T. and L. Hoffmann. 2005. Roaring Fork Watershed Inventory. The Roaring Fork Conservancy. http://www.roaringfork.org. Accessed March 1, 2006.

O'Keefe, T. and L. Hoffmann. 2003. Roaring Fork Watershed Inventory. The Roaring Fork Conservancy. http://www.roaringfork.org. Accessed August 11, 2004.

Parmesan, C. 1996. Climate and species range. *Nature* 382:765-766.

Patwardhan, A. 2006. Assessing vulnerability to climate change: The link between objectives and assessment. *Current Science* 90(3):376-383.

Peet, R. K. 1981. Forest vegetation of the northern Colorado Front Range: Composition and dynamics. *Vegetatio* 45:3-75. Pitkin County. 2005. North Star Nature Preserve: 2000 Resource Management Plan. Updated June 27, 2005.

Pitkin County. 2005. Noxious Weed Management Plan. Prepared in 1999 and revised in Spring 2005.

Platt, R.V. 2004. Global and local analysis of fragmentation in a mountain region of Colorado. *Agriculture Ecosystems & Environment* 101:207-218.

Prentice, I. C. 1992. Climate change and long-term vegetation dynamics. Pages 293-339 in D. C. Glenn-Lewin, R. A. Peet, and T. Veblen, editors. Plant succession: theory and prediction. Chapman & Hall, New York.

Price, J. 1995. Potential impacts of global climate change on the summer distribution of some North American grasslands birds. Ph.D. dissertation. 540 p. Wayne State University, Detroit, Mich.

Price, M. F., and J. R. Haslett. 1995. Climate Change and Mountain Ecosystems. Pages 73-97 in N. J. R. Allan, editor. Mountains at risk: current issues in environmental studies. Manohar Publishers & Distributors, New Delhi.

Ptacek, J.A., D.E. Rees, and W.J. Miller. 2003. A Study of the Ecological Processes of the Fryingpan and Roaring Fork Rivers Related to the Operation of Ruedi Reservoir. Prepared by Miller Ecological Consultants, Inc. for the Roaring Fork Conservancy. June. http://www.roaringfork.org. Accessed August 11, 2004.

Reiners, W.A. et al. 2003. Natural ecosystems I: The Rocky Mountains. In *Rocky Mountain/Great Basin Regional Climate-Change Assessment*, F.H. Wagner (ed.). Report for the U.S. Global Change Research Program. Utah State University, Logan, pp. 145-184.

Richardson, R. B. and J. B. Loomis. 2005. Climate change and recreation benefits in an alpine national park. *Journal of Leisure Research* 37(3): 307-320.

Ricklefs, R. E., and G. L. Miller. 2000. Ecology. W.H. Freeman & Co., New York.

Roberts, L. 1989. How Fast Can Trees Migrate? *Science* 243:735-737.

Saunders, S., and M. Maxwell 2005. Less Snow, Less Water: Climate Disruption in the West. The Rocky Mountain Climate Organization.

Schröter, D. 2005. Vulnerability to Changes in Ecosystem Services. CID Graduate Student and Postdoctoral Fellow. Working Paper No. 10. July. www.cid.harvard.edu/cidwp/pdf/grad_student/010.pdf. Accessed 11/2/2005.

Schrupp, D. L., W. A. Reiners, T. Thompson, F. D'Erschia, T. Owens, K. Driese, C. Buoy, A. Cade, J. Kindler, J. Lowsky, L. O'Brien, L. Satcowitz, M. Wunder, J. Stark, and S. Russo 2002. Colorado Gap Analysis Program: A Geographic Approach to Planning for Biological Diversity - Final Report. USGS Biological Resources Division, National Gap Analysis Program and Colorado Division of Wildlife, Moscow, ID.

Scott, J. M., F. Davis, B. Csuti, R. Noss, B. Butterfield, C. Groves, H. Anderson, S. Caicco, F. D'Erchia, J. T.C. Edwards, J. Ulliman, and G. Wright. 1993. Gap analysis: A geographic approach to protection of biological diversity. Wildlife Monographs 123.

Scott, D., G. McBoyle, and B. Mills. 2003. Climate change and the skiing industry in southern Ontario (Canada): Exploring the importance of snowmaking as a technical adaptation. *Climate Research* 23(2):171-181.

Sloan, Chrissy. 2004. The Effect of the Shoshone and Cameo Calls on the Roaring Fork Watershed. The Roaring Fork Conservancy, December. www.roaringfork.org/images/other/shoshone.pdf. Accessed March 23, 2006.

Smith, J. B., and D. A. Tirpak 1990. The Potential effects of global climate change on the United States. Hemisphere Pub. Corp., New York.

Smith, J.B. and M. Hulme. 1998. Climate change scenarios. In *Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies*, J. Feenstra, I. Burton, J.B. Smith, and R. Tol (eds.). Institute for Environmental Studies, Free University, Amsterdam. Available http://www.vu.nl/english/o_o/instituten/IVM/pdf/handbook_climat.pdf.

REFERENCES

Smith, T. M., H. H. Shugart, G. B. Bonan, and J. B. Smith. 1992. Page 337 in F. I. Woodward, editor. The ecological consequences of global climate change: Advances in ecological research. Academic Press, London; San Diego.

Sprugel, D. G. 1991. Disturbance, equilibrium, and environmental variability: What is natural vegetation in a changing environment? *Biological Conservation* 58:1-18.

Street, R. B., and S. M. Semenov. 1990. Natural Terrestrial Ecosystems. Pages 311-344 in W. J. M. Tegart, G. Sheldon, and D. C. Griffiths, editors. Climate change: the IPCC impacts assessment. Intergovernmental Panel on Climate Change, Working Group II. Australian Government Publishing Service, Canberra.

T. Hickey, A., J.C. Emerick, and K.E. Kolm. 2000. Preliminary Hydrologic and Biological Characterization of the North Star Preserve, Pitkin County, Colorado. Submitted to the Pitkin County Board of Commissioners and the Aspen City Council by Colorado School of Mines. May.

Taylor, G. H., and C. Daly. 1998. Parameter-elevation Regressions on Independent Slopes Model (PRISM) derived polygon coverages of average monthly and annual precipitation for the climatological period 1961-1990. Water and Climate Center of the Natural Resources Conservation Service. Portland, OR. Available online at http://www.ocs.orst.edu/prism/prism_new.html.Tebaldi, C., R.L. Smith, R.L., D. Nychka and L.O. Mearns (2005) "Quantifying uncertainty in projections of regional climate change: a Bayesian approach to the analysis of multimodel ensembles -- *J. of Climate*, vol. 18, no. 10, pp. 1524-1540.

Tebaldi, C., L.O. Mearns, D. Nychka and R.L. Smith (2004) "Regional probabilities of precipitation change: a Bayesian analysis of multimodel simulations -- *Geophys. Research Letters*, vol. 31.

The Green Room: The Ski Industry Environmental Database. 2005. http://www.nsaa.org/nsaa/environment/the_greenroom/index.asp?mode=greenroom&mode2=full&caseid=697&topic=T04 Accessed March 23, 2006.

Thomas, C. D., and J. J. Lennon. 1999. Birds extend their ranges northwards. *Nature* 399:213.

Thompson, T., P. Gillard, K. Driese, W. A. Reiners, R. Thurston, and D. Schrupp 1996. Manual to Accompany The Gap Analysis Land Cover Map of Colorado. Colorado Division of Wildlife, Denver, CO.

Urquhart, Janet. 2004. "Aspen Power's Electrifying Tale." *The Aspen Times*. September 20. http://72.14.203.104/search?q=cache:WSu3GjNfGmcJ:aspentimes.com/article/20040920/AROUND08/109200006/0/AROUND04+ASpen+times+urquhart+power+electrifying+tale&hl=en&gl=us&ct=clnk&cd=1. Accessed February 21, 2006.

Urquhart, Janet. 2002. "Roaring Fork River Silenced." The Aspen Times. August 20. http://72.14.203.104/search?q=cache:6oKMEuG7ss4J:www.aspentimes.com/apps/pbcs.dll/artikkel%3FSearchID%3D73108242547328%26Avis%3DAT%26Dato%3D20020820%26Kategori%3DNEWS%26Lopenr%3D208190001%26Ref%3DAR+Roaring+fork+river+silenced+aspen+times&hl=en&gl=us&ct=clnk&cd=1. Accessed February 21, 2006.

U.S. Bureau of Reclamation. 1983. Fryingpan-Arkansas Project: Ruedi Reservoir, Colorado Round II Water Sale Environmental Assessment. Prepared by Simons, Li & Associates, Inc. for the U.S. Department of Interior, Fort Collins, CO.

U.S. Water News Online. 2005. "Colorado residents do their part to save water" http://www.uswaternews.com/archive/arcconserv/5coloresi8.html. August. February 6, 2006.

USDA. 2005. Background – European Gypsy Moth. USDA – Animal and Plant Health Inspection Service (APHIS). Available: http://www.aphis.usda.gov/ppq/ispm/gm/egm-background.html. Accessed January 5, 2006.

USDA Forest Service. 2005. Draft Supplemental Environmental Impact Statement: Baylor Park Blowdown. Sopris and Rifle Ranger Districts; White River National Forest; Mesa, Garfield, and Pitkin Counties, Colorado. February.

USDA Forest Service. 1981. Instream Flow Recommendations for Lincoln Creek and the Roaring Fork River.

USGS. 2000. Colorado Land Cover Data Set, Edition: 1 (1992) Raster Digital Data. Sioux Falls, SD. Available: http://seamless.usgs.gov/website/seamless/viewer.php. Accessed 11/21/2005.

USGS. 2004. WEBMAP.LANDSAT_LZ77 (Landsat Orthoimagery Mosaic). *Edition:* 0.1. Remote-Sensing Image. Sioux Falls, SD. Available: http://seamless.usgs.gov. Accessed 11/30/2005.

USGS EROS Data Center. 1999. USGS 30 Meter Resolution, One-Sixtieth Degree National Elevation Dataset for CONUS, Alaska, Hawaii, Puerto Rico, and the U.S. Virgin Islands. Edition 1. Raster Digital Data. Sioux Falls, SD. U.S. Geological Survey.

USGS EROS Data Center. 2001. Landsat ETM+ level-1G SLC-off gap-filled remote sensing image. USGS/EROS, Sioux Falls, SD.

USGS LP DAAC. 2004. 2001 ASTER Remote Sensing Image. Sioux Falls, SD. Geological Survey, Land Processes Distributed Active Archive Center (LP DAAC). Available: http://lpdaac.usgs.gov. Accessed 8/2/2005.

Wagner, F.H. 2003. Outdoor recreation and tourism. In *Rocky Mountain/Great Basin Regional Climate-Change Assessment*, F.H. Wagner (ed.). Report for the U.S. Global Change Research Program. Utah State University, Logan, pp. 1131-1144.

Watson, R. T., M. C. Zinyowera, and R. H. Moss 1997. The regional impacts of climate change: an assessment of vulnerability. Cambridge University Press, New York.

Weisberg, P. J., and W. L. Baker. 1995. Spatial variation in tree seedling and krummholz growth in the forest-tundra ecotone of Rocky Mountain National Park, Colorado. Arctic and Alpine Research 27.

Whetton, P. H., M. R. Haylock, and R. Galloway. 1996. Climate change and snow-cover duration in the Australian Alps. *Climatic Change* 32(4):447-479.

Whittaker, R. H. 1975. Communities and Ecosystems. Macmillan, London.

Whittaker, R. H., and W. A. Niering. 1975. Vegetation of Santa Catalina Mountains, Arizona. V: Biomass, production, and diversity along the elevation gradient. Ecology 56:771–790.

Wigley, T.M.L. 2004. MAGICC/SCENGEN. National Center for Atmospheric Research, Boulder, CO. http://www.cgd.ucar.edu/cas/wigley/magicc/.

Wigley, T.M.L. 1988. Changes in the risk of occurrence of an extreme event within 100 years due to a trend in the mean. *Climate Monitor* 17(2):43-55.

Winward, A. H., and Colorado Division of Wildlife 2004. Sagebrush of Colorado : taxonomy, distribution, ecology & management. Colorado Division of Wildlife, Department of Natural Resources, Denver, CO.

Ziska, L.H. 2003. Evaluation of the growth response of six invasive species to past, present and future atmospheric carbon dioxide. *Journal of Experimental Botany,* Vol. 54, No. 381, pp. 395-404.

AGCI
100 East Francis Street
Aspen CO 81611
http://www.agci.org
970 925 7376
agcimail@agci.org

ISBN 0-9741467-3-0

ISBN 0-9741467-3-0
90000>
9 780974 146737

THIS PUBLICATION IS PART OF THE
ASPEN GLOBAL CHANGE INSTITUTE'S ELEMENTS OF CHANGE SERIES