The Impact of Climate Change on the Ski Industry in Colorado and California

by
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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Climate change is considered one of the primary threats to the sustainability of ski tourism around the world. Studies in several countries project the ski industry will be impacted by shorter ski seasons, greater snowmaking requirements, and a declining ski demand. Many supply-side studies suffer key limitations, such as the omission of snowmaking, leaving their conclusions highly questionable. This study utilizes the SkiSim 2 model to reassess the implications of projected climate change for two major ski tourism destinations in the Western USA (Vail, Colorado and Lake Tahoe, California) where previous studies projected major impacts when snowmaking was not considered. Historical climate data (1961-1990) and the stochastic weather generator LARS-WG are used to examine the impact of climate change scenarios for ski season length and snowmaking requirements by the 2050s. Comparisons with previous studies and implications for ski tourism development and planning will be discussed.

Acknowledgements

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Dedication

This thesis is dedicated to Tiffany Winton. Throughout my graduate work you have been my girlfriend, fiancé and wife, above all else you have always been my best friend and the person I relied on most. Thank you for everything you sacrificed to make this work possible.

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List of Abbreviations

AR4- Fourth Assessment Report
AR5- Assessment Report Five
CDM- Clean Development Mechanisms
CSCUSA- Colorado Ski Country USA
CCCMA- Canadian Centre for Climate Modeling and Analysis
DAI- Dangerous Anthropogenic Interference
DJF – December, January, February
FAR- First Assessment Report
GDP- Gross Domestic Product
GHG – Greenhouse Gases
GISS- Goddard Institute for Space Studies
HADCM3 – Hadley Center Climate Model 3
IPCC-Intergovernmental Panel on Climate Change
IPSL- Institut Pierre Simon Laplace
Kottke- Kottke National End of Season Survey
LARS-WG – Long Ashton Research Station Weather Generator
M - Metres
MASL- Metres Above Sea level
MIROC- Model for Interdisciplinary Research on Climate
Mt CO_2 – Metric Tonne Carbon Dioxide
NCDC- National Climatic Data Centre
NH – Northern Hemisphere
NOAA- National Oceanic Atmospheric Administration
Non-GHG- Non-Greenhouse Gases
NRDC- National Resources Defense Council
NSAA- National Ski Areas Association
NT – North Tyrol
OECD – Organization for Economic Co-operation Development
PCIC – Pacific Climate Impacts Consortium
PCM – Parallel Climate Model
PP - Page
PPM- Parts Per Million
PROD_SNOW – Produced Snow
RCP- Representative Concentration Pathways
REQ_SNOW – Required Snow
RF- Radiative Forcing
SAR- Second Assessment Report
SCA – Snow Covered Area
SIDS- Small Island Developing States
SRES- Special Report on Emission Scenarios
ST – South Tyrol
SWE – Snow Water Equivalent
TAR- Third Assessment Report
UNCED- United Nations Conference on Environment and Development
UNEP- United Nations Environment Programme

UNFCCC- United Nations Framework Convention on Climate Change
USD- United States Dollars
UNWTO- United Nations World Tourism Organization
WEF – World Economic Forum
WTTC- World Travel and Tourism Council
WMO- World Meteorological Organization

1. Introduction

Study Context and Rationale

Upon release of their Fourth Assessment Report (AR4) (2007a) the Intergovernmental Panel on Climate Change (IPCC) stated that between the 1850-1899 and 2001-05 periods global average temperature rose by 0.76°C (IPCC 2007a). This increase has not been linear, as “the ten hottest years on record have all occurred since 1998; and 18 of the last 21 years feature among the 20 warmest years on record since (reliable) recording of temperature started in 1880” (UNEP 2012). The impact of this warming will continue to be felt globally for decades, if not centuries, to come (IPCC 2007a). Current examples of its impact on natural systems include drought, increased extreme weather events, flooding and sea-level rise, and decreased ice and snow covered areas (IPCC 2007a). These will result in impacts to human systems such as agriculture, health care, insurance, energy, transportation and tourism (IPCC 2007b). However, the degree to which impacts occur will vary according to the level of change experienced as well as the level of dependence those systems have on current average climate (IPCC 2007a). This study seeks to examine the potential impact of climate change on ski operations in the western United States of America.

The global tourism industry has been identified as at risk from potential climate change due to its reliance on current regional climate in providing consistent conditions suitable for tourism pursuits (Scott, Amelung, Becken, Ceron, Dubois, Gossling, Peeters & Simpson 2008a). The ski tourism industry has been identified as particularly at risk due to its dependence on weather in providing its snow-based product (Scott, McBoyle & Mills 2003, Scott, Dawson & Jones 2008b). Without consistent below freezing temperatures and adequate snowfall, the ski industry will struggle to remain operable; both of these are projected to be adversely impacted by climate projections in many ski tourism regions.

Numerous studies have sought to examine the relationship between global climate change and its impact on ski operations, with the majority projecting substantial adverse impacts (Scott, Hall and Gossling 2012a). In general, the literature projects reductions to season length and snowfall, increased requirements for artificial snow, an increased likelihood of avalanche occurrence, and degraded quality of conditions, which are all likely to result in increased operating costs and reduced demand (Scott 2005, Scott et. al. 2012a).

When examining this literature a common limitation amongst vulnerability assessments is the inclusion of adaptation strategies in response to projected climate change (Scott & McBoyle 2007). Specifically, the use of snowmaking as an adaptation strategy has only been considered in a small number of studies (Scott & McBoyle 2007; Scott, Hall & Gossling 2012b). Studies that consider this adaptation strategy found that when snowmaking is included, impacts to season length are significantly reduced (Scott, McBoyle & Mills 2003, Scott, McBoyle & Minoque 2007a, Scott et. al. 2008b, Steiger 2010). Some studies suggest that even under the warmest climate change scenarios through the 2050s or late 21st century in some areas, ski season length can be preserved with adequate snowmaking capacity (Scott & McBoyle 2007).

The ski industry in the western United States is yet to be the focus of extensive research on the potential impacts to ski operations from climate change (Scott et. al. 2012b). This is surprising considering that the ski tourism market in North America is the second largest in the world, registering 60.5 million skier visits in 2010/11, trailing only the European Alps (NSAA 2011b, Scott et. al. 2012b). Cumulatively, skier visits in 2010/11 in the western USA ski regions were the highest in the nation at 33.1 million (the Rocky Mountain region accounted for 20.9 million skier visits while the Pacific West region registered 12.1 million skier visits) (NSAA 2011b). According to the National Ski Areas Association (NSAA), at the national level, ski areas generated an average of $25.7 million in gross revenue per resort in 2010/11 (NSAA 2011b). In the Rocky Mountain and Pacific West ski regions, average gross revenue per resort was $39.1 and $22.3 million in 2010/11, respectively (NSAA 2011c). Extrapolating these figures, cumulatively ski areas in the Rocky Mountain region (96 resorts) grossed $3.8 billion in revenue, while cumulatively ski areas in the Pacific West region (76 resorts) grossed $1.7 billion in revenue in the 2010/11 season.

To date, all known assessments of the impacts of climate change on ski operations in the western United States have not included snowmaking as an adaptation strategy. In fact, most research in the region, some of which does has garnered much media attention, does not directly model ski operations at all. Instead, these studies have examined climate change impacts that could indirectly impact ski operations using indicators such as snow water equivalent (SWE), stream flow, and avalanche occurrence (Lazar and Williams 2008, Battaglin, Hay & Markstrom 2011, Woodford, Quartarone, Berg and Erickson 1998, Zimmerman, O'Brady and Hurlbrutt 2006, Hayhoe, Cayan, Field, Frumhoff, Maurer, Miller, Moser, Schneider, Cahill, Cleland, Dale, Drapek, Haneman, Kalkstein, Lenihan, Lunch, Neilson, Sheridan & Verille 2004). The media's 'Doom and Gloom' depiction of ski operations under climatically warmer futures further threatens this industry in these locations, with captions including "Colorado's Ski Industry Could 'Melt Away'" (Berwyn 2009) and "Climate Change: The End of Sierra Skiing?" (Alameda Patch 2012).

This study constitutes the first study to examine the potential impact of climate change on the ski tourism industry in the western United States using a state of the art ski operations model. It builds on the work of Scott et. al. (2003, 2006, 2007a, 2008a) that developed the SkiSim 1 model for eastern North America and the work of Steiger (2010, 2011) that refined the SkiSim model (SkiSim 2) for application in Tyrol and the broader European Alps. In this study, the revised SkiSim 2 model is adapted and tested in two study areas in Colorado and one in California (Vail, Copper Mountain, Squaw Valley).

Goals and Objectives

The principal goal of this research is to examine the extent to which projected climate change could impact ski operations, including the capability of snowmaking in minimizing season length loss. Following this, a reassessment of previous claims in the literature and media about climate change impacts on the ski industry in these regions is conducted.

Five objectives have been identified in attempting to reach this goal;

1. Calibrate SkiSim 2 to successfully model snowfall as well as snowmelt in the baseline climate period (1961-1990) at three study areas.
2. Validate the SkiSim 2 model's ability to represent historical skiable days, snow days and season length in the baseline climate period at three study areas.
3. Model season length at specified elevations of the ski hill under the selected climate change scenarios, both inclusive and exclusive of snowmaking.

4. Model the potential to produce artificial snow under climate change scenarios and with current technological capacity.
5. Reassess previous claims on the impacts to ski operations from climate change in the selected study areas.

Structure of Thesis

This thesis is organized into six chapters: Introduction, Literature Review, Methods, Results, Discussion and Conclusion. The first chapter provides context for the study and the rationale for why this work was undertaken. It also sets out all objectives of the research. Chapter 2 provides a literature review that includes a summary of global climate change, a review of the tourism industry and ski tourism, and concludes by discussing the influence of climate and climate change on tourism, with a particular focus on ski tourism. Chapter 3 outlines the methodological approach taken in this research. It includes information on the case study locations and the importance of the ski industry in these locations, as well as data sources and an overview of the modeling approach. Chapter 4 summarizes the results from SkiSim 2 modeling and includes projections of ski operations under 2050s climate change scenarios. This includes projections for ski season length, impacts to individual season segments (e.g. Early season, Christmas/New Years Period, School Holidays), and snowmaking. Chapter 5 compares the findings against previous studies in the region and media claims and discusses the implications for the future viability of the ski industry at these destinations. Chapter 6 concludes the thesis with suggestions for future research.

2. Literature Review

Introduction

This chapter reviews the major bodies of literature consulted for this study. The areas of research drawn upon include: climate change, tourism industry development trends and challenges, and the relationship between tourism and climate change. This chapter is divided into four main sections, each highlighting different aspects of the above bodies of literature. It begins with an overview of the global climate change issue; including a description of its development as an issue, the level of climate change recorded to date and projections of future change. Following this, the tourism literature is examined beginning with an overview of the global industry then focusing more definitively on the ski tourism industry and its place in the selected case study regions. The third section provides a conceptual framework for the study and delves into the relationship between climate change and tourism looking at how they influence and are influenced by each other. Finally, the chapter concludes with a section devoted specifically to climate change and the ski industry reviewing projected impacts and adaptation strategies.

Climate Change

Development of an International Climate Governance Regime

In 2007, the IPCC released their AR4 and stated that "warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea levels" (IPCC 2007a, pp. 5). These changes, albeit non-linear, have occurred since the onset of the industrial revolution and are largely attributable to the increased concentration of global greenhouse gases (GHG) (IPCC 2007a). Global climate change is measured relative to the pre-industrial era since this period is when humans began their most discernible impact on the global atmosphere and climate system.

Within this field, Joseph Fourier, in 1824, "determined that the earth would be far colder if it lacked an atmosphere", being the first to describe the natural greenhouse effect (Scott et. al. 2012b, pp. 18). This term denotes the Earth's atmosphere acting in the same manner as a greenhouse; energy from the sun enters but due to built up emissions cannot escape, thus becoming trapped. Despite this early work, it was not until the 1980s that human-induced climate change became widely publicized and of significant importance to national and international political bodies (Bodansky 2001). Swedish chemist, Svante Arrhenius, in 1896 published the first calculation of potential global warming as a result of anthropogenic CO_2 emissions (Bulkeley & Newton 2010). His work built upon the burgeoning scientific field that examined global temperatures, the atmosphere and the idea that atmospheric gases have the varying ability to absorb and/or transmit radiant heat (Bulkeley & Newton 2010, Scott et. al. 2012b).

The initial development of an international climate change governance regime began in the 1980s with “the discovery of the stratospheric ‘ozone hole’ and the publication of the Brundtland Commission report, Our Common Future” (Bodansky 2001, pp. 23). Throughout the 1980s a general scientific consensus was reached that increased anthropogenic emissions of GHG, and other radiatively active non-GHG, are enhancing the Earth’s natural ‘Greenhouse Effect’ (Bulkeley & Newtown 2010). The development of this issue culminated in the 1992 United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, Brazil.

This meeting resulted in the creation of an international agreement on climate change, called the United Nations Framework Convention on Climate Change (UNFCCC) (United Nations 1992). The convention’s stated objective “is to achieve the stabilization of the greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference (DAI) with the climate system” (United Nations 1992, pp. 4). In 1997, the Kyoto Protocol was created as the policy tool enlisted to achieve some objectives of the UNFCCC (UNFCCC 2012). It entered into force in 2005 and broadly required industrialized nations to restrict and/or reduce national emissions to a level lower than what was recorded in 1990, which for most industrialized countries equates to a 5% reduction (UNFCCC 2012).

The IPCC is the international scientific body tasked with the continual assessment of global climate change (IPCC 2012a). Established in 1988, through the United Nations Environment Programme (UNEP) and the World Meteorological Organisation (WMO), the IPCC is intended to “provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts" (IPCC 2012a). The IPCC provides scientific assessment reports, of which there have been four (1990, 1995, 2001, 2007), on the state of climate change.

Changes in Major Atmospheric Constituents

As aforementioned, climate change since the industrial revolution is the result of increased anthropogenic emissions of GHGs (IPCC 2007a). CO_2 concentrations (the current value is 379 ppm (2005) while in 1750 CO_2 concentrations were 280 ppm) have surpassed "the natural range over the last 650,000 years (180 to 300 ppm)" (IPCC 2007a, pp. 2). In addition to CO_2, aerosols and other GHG and non-greenhouse gases (non-GHG) also impact global energy balance (both positively and negatively), these include Methane and Nitrous Oxide as well as gases such as sulphates, nitrates, organic carbon and black carbon (IPCC 2007a). "The combined anthropogenic radiative forcing is estimated to be at +1.6 [-1.0 - +0.8] Wm-2, indicating that since 1750, it is extremely likely that humans have exerted a substantial warming influence on the climate" (Forster, Ramaswamy, Artaxo, Bernsten, Betts, Fahey, Haywood, Lean, Lowe, Myhre, Nganga, Prinn, Raga, Schulz and Van Dorland 2007, pp. 131).

In their Summary for Policymakers, the IPCC (2007a) stated that the primary source of this increase in radiative forcing relates to fossil-fuel consumption, followed by land-use change. As noted by the IPCC in AR4, "it is extremely unlikely that global climate change of the past 50 years can be explained without external forcing, and very likely that it is not due to known natural causes alone" (IPCC 2007a, pp. 10).

Climate Change Observations

Upon the release of AR4, the IPCC stated that the global average temperature has increased 0.76°C since 1850-1899 (IPCC 2007a). Other changes include ocean temperature increase, glacier and snow cover decreases, while extreme weather has increased in frequency and severity (IPCC 2007a, IPCC 2012). Altered precipitation patterns are also of tremendous importance as they affect many natural and human systems.

Of particular relevance to this work, "mountain glaciers and snow cover have declined in both hemispheres" (IPCC 2007a, p. 5). In AR4, it was stated that "snow cover has decreased in most regions…Northern Hemisphere (NH) snow cover observed by satellite over the 1965 to 2005 period decreased in every month except November and December, with a stepwise drop of 5% in the annual mean in the late 1980s" (Lemke, Ren, Alley, Allison, Carrasco, Flato, Fujii, Kaser, Mote, Thomas & Zhang 2007). Snow covered areas (SCA) have had important changes; "(1) a shift in the month of maximum snow cover from February to January, (2) a statistically significant decline in annual mean SCA, (3) a shift towards earlier spring melt by almost two weeks in the 1972 to 2003 period (Lemke et. al. 2007). In North America, SCA decreases have been largely confined to the 1950-2004 period, continuing thereafter (Lemke et. al. 2007). SCA actually increased throughout November to January between 1914-2004, however, of relevance to this study, SCA decreased most substantially in the spring months over western North America (Lemke et. al. 2007). This last observation will have significant implications for ski tourism, carrying the potential to reduce ski season length.

Projections of 21st Century Climate Change

In AR4, the IPCC projected changes to earth systems from a broad range of GHG emissions scenarios and climate models. Projections in AR4 vary according to the GHG emissions scenarios and climate model utilized, however, all include an uncertainty range that provides the 'likely ranges' of potential change. The IPCC Special Report on Emission Scenarios (SRES) provided scenarios of emissions comprised of four different narratives that consider the many and diverging relationships between GHG emissions and their driving forces; listed as demographic, economic, and technological change (IPCC 2000). The SRES formulation process resulted in 40 distinct scenarios being grouped into four 'scenario families' (A1, A2, B1, B2) (IPCC 2000), which are all equally valid with no discrepancy or emphasis on the likelihood of occurrence (IPCC 2000). These scenarios are employed in the current study

For temperature increase by 2100, the 'likely range' is between 1.8°C (B1) and 4.0°C (A1Fi) for global surface average temperature (IPCC 2007a). Temperature warming projections for western North America show a greater degree of warming anticipated relative to global projections, while also projecting slightly higher temperatures during the winter months (DJF) than the remainder of the year (Christensen, Hewitson, Busuloc, Chen, Gao, Held, Jones, Kolli, Kwon, Laprise, Magana Rueda, Mearns, Menendez, Ralsanen, Rinke, Sarr & Whetton 2007). Annual warming throughout western North America by 2100 is projected to range 2.1°C to 5.7°C (A1B), while DJF temperature is expected to increase by 1.6°C to 5.8°C (A1B) (Christensen et. al. 2007).

It is unlikely that in the coming decades and centuries the warming trend will cease as anthropogenic emissions of GHGs continue to rise (IPCC 2007a). To highlight this point, if GHG concentrations were held at year 2000 values, average global surface temperatures would increase by an additional 0.6° C (0.3°-0.9°) by 2100 (IPCC 2007a). This warming would be the result of past emissions only and is referred to as the 'committed warming projection' (IPCC 2007a). The extent to which global temperatures fluctuate within these spectrums is dependent on the level of continued emissions and the complex interactions within the climate system.

Mitigation and Adaptation

Any discussion on climate change necessitates a dialogue on the strategies to manage climate change and the advantages and disadvantages of adaptation and mitigation. According to the IPCC, in relation to climate change, adaptation refers to "initiatives and measures to reduce the vulnerability of natural and human systems against actual or expected climate change effects" (IPCC 2012b, pp. 76). The IPCC notes that different types of adaptation strategies are possible, including "anticipatory and reactive, private and public, and autonomous and planned" (IPCC 2012b, pp. 76). Conversely, mitigation is defined by the IPCC as "technological change and substitution that reduce resource inputs and emissions per unit of output. Although several social, economic and technological policies would produce an emission reduction, with respect to climate change, mitigation means implementing policies to reduce greenhouse gas emissions and enhance sinks" (IPCC 2012b, pp. 84).

There are four key assessments to consider: (1) vulnerability to climate change, defined as "the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change" (IPCC 2012b, pp. 89). (2) Climate change resilience, defined as the ability to "absorb disturbances while retaining the same basic structure and ways of functioning" (IPCC 2012b, pp.86). (3) Sensitivity to climate change, defined as the "degree to which a system is affected, either adversely or beneficially by climate variability or climate change" (IPCC 2012b, pp. 86). (4) Lastly, adaptive capacity, defined as "the whole of capabilities, resources, and institutions of a country or region to implement effective adaptation measures" (IPCC 2012b, pp. 76).

Debates have arisen over the merits of each approach and have largely focused on cost-benefit analysis in conjunction with the level of disruption to society each would incur (Biesbroek et. al. 2009). Mitigation is regarded as a proactive approach to the issue as it reduces the overall level of change to be experienced. As such, actions of this nature would serve to reduce natural and human systems' vulnerability to climate change. However, despite complete mitigation of emissions the earth is still committed to a certain degree warming, thus some form of adaptation in the future will be unavoidable (Biesbroek et. al. 2009). Adaptation will allow a system's resilience to climate change to be enhanced, thus reducing its sensitivity to adverse impacts and increasing the likelihood of benefiting from potential changes. The success of adaptation strategies will depend on the system's level of adaptive capacity, which is likely to vary between regions and systems. Academics and policy makers have agreed that adaptation and mitigation must occur in conjunction with each other to effectively reduce the adverse impacts associated with anthropogenic climate change (Beisbroek et. al. 2009).

Tourism

Tourism Sector Overview and Development Trends

Global

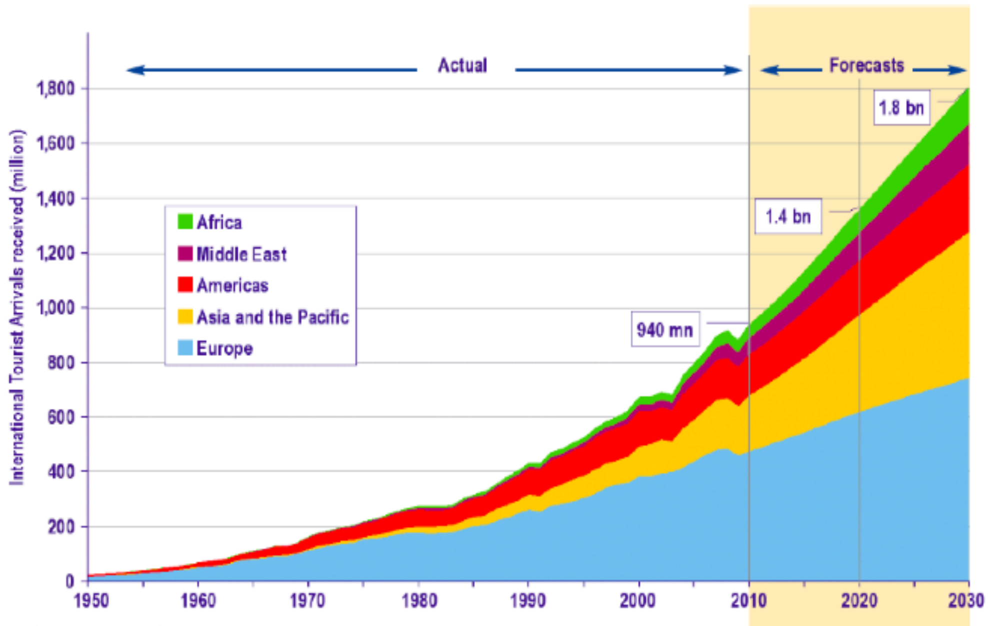
The World Tourism Organization (UNWTO) defines tourism as a "social, cultural and economic phenomenon which entails the movement of people to countries or places outside their usual environment for personal or business/professional purposes" (UNWTO 2012a). Tourism is one of the world's largest economic sectors with every country offering some form of attraction in an attempt to generate revenues and increase awareness of social and cultural identities (UNWTO 2009a). Travel and tourism are especially important for developing countries and have been a focus of the United Nation's Millennium Development Goals; "tourism is an effective way of redistributing wealth and a catalyst for gender equality, cultural preservation and nature conservation" (UNWTO 2009a, pp. 2).

In 2011, global international tourist arrivals – defined as the global number of non-resident arrivals to a country of reference - grew to 983 million, surpassing the previous record set in pre-recession 2008 by 61 million (UNWTO 2012b). Despite a drop in travel during 2009, average annual growth for international arrivals was recorded at 3.5% over the 2005 - 2011 period (UNWTO 2012b). These trends continue those over the 20th and 21st centuries, where international arrivals have increased at a remarkable rate; increasing by 6.5% per year over the 1950-2005 period (Figure 2.1) (UNWTO 2011). The expansion of international tourism reflects growth in the global economy and population. As the global economy diversified, a larger percentage of the global population attained the wealth required to participate in tourism. This growth was also assisted by advancements in transportation, and specifically aviation, technology (UNWTO 2012b).

Economically, the global tourism industry generates substantial revenues. 2011 arrivals resulted in estimated international tourism receipts of $1030 billion (USD) – international tourism receipts are a proxy for expenditures for inbound international tourists, and include payments to national carriers for international transport as well as any prepayment for goods and services (World Bank 2012). As a percentage of global gross domestic product (GDP) the international tourism industry contributed approximately 5% in 2011 (UNWTO 2012b). The World Travel & Tourism Council (WTTC) (2012) states that in 2011 the international tourism industry contributed $6,346 billion (USD) to global GDP, representing 9.1% of global GDP when including direct, indirect and induced impacts. The overall number of jobs in 2011 attributable to the international tourism industry is approximated between 6-7% globally by the UNWTO, an estimation that grows to 8.7% of global employment according to the WTTC (UNWTO 2012b; WTTC 2012).

Projections for future growth in this industry foresee that emerging economies will become the dominant source of growth in international tourist arrivals; “the market share of emerging economies has increased from 30% in 1980 to 47% in 2011, and is expected to reach 57% in 2030” (Figure 2.1) (UNWTO 2012b, pp. 2). As individuals in these nations gain the wealth necessary for travel, international arrivals are expected to increase.

Figure 2.1: Growth and Projections of Growth in International Tourists Arrivals



Source: UNWTO 2012

North America

Tourism is an important mainstay North America's economy and lifestyle, it experienced similar growth as described above over the 20th and 21st centuries. International arrivals in North America grew to 101.7 million in 2011, beating all other sub-regions within the Americas by 74.9 million international arrivals, comprising 10.3% of the global market share (UNWTO 2012b). Unsurprisingly, in 2011 the USA (62.3 million) recorded the largest number of international arrivals compared to Canada (15.9 million) or Mexico (23.4 million) (UNWTO 2012b). These three countries are each other's largest source markets for international arrivals (UNWTO 2011b).

United States of America

A map of the USA, including a depiction of where the major ski areas examined in this study are located, is provided in Figure 2.2. The USA has experienced the same long-term expansion of its tourism industry since 1950. Tourism has become one of the nation's highest earning economic sectors, generating $1.2 trillion in total (both international and domestic) tourism related sales in 2011 (2.7% of the national GDP) (Office of Travel and Tourism Industries 2012). Additionally, the travel and tourism industry provided 7.6 million jobs in 2011, 5.4 million of those directly in the tourism industry (Office of Travel and Tourism Industries 2012). Domestic tourism in the USA is important to the ski tourism industry as it represents the largest share of visitors to American ski areas (Longwoods International 2001, Office of Travel and Tourism Industries 2012).

Figure 2.2: Map of USA with Case Study Ski Areas

Source: google.com

Colorado

Colorado is located in the central plains of America (Colorado Tourism Office 2012). Its western regions become engulfed by the Rocky Mountains and are home to 54 peaks that exceed 4200 metres above sea-level (masl) (Colorado Tourism Office 2012). Colorado encompasses an area of 268,627 square kilometers and has a population slightly over 5 million people (Colorado Tourism Office 2012). The state tourism board touts Colorado as "a four season destination offering world-class adventure and recreational pursuits, a thriving arts scene, a rich cultural heritage, flavorful cuisine and renowned ski resort areas." (Colorado Tourism Office 2012).

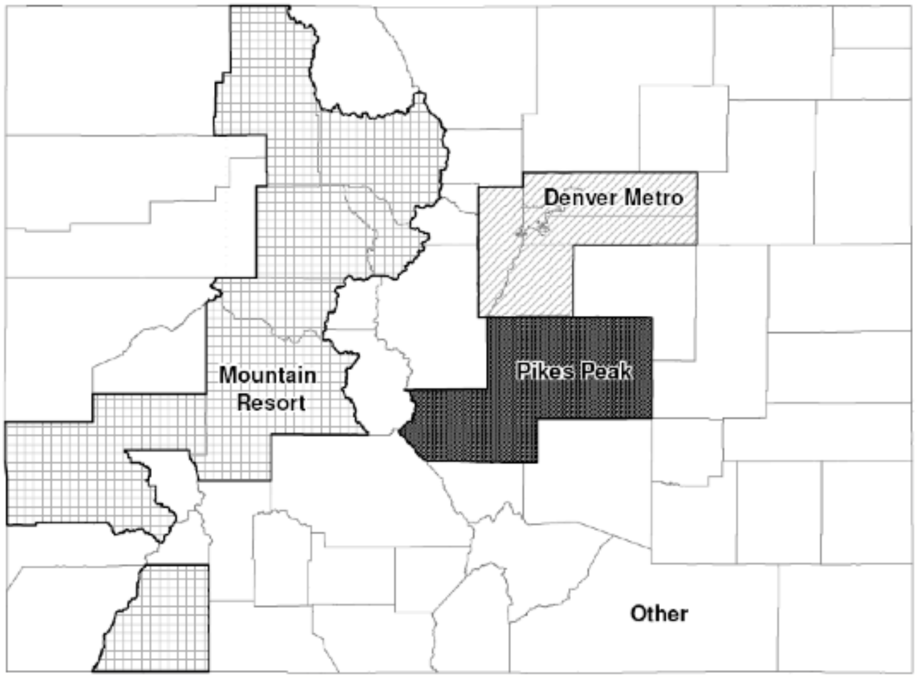
In 2010, Colorado recorded 28.9 million overnight trips, a new state record (Longwoods International 2011). This was echoed by a 9% increase in day trips to and within the state, reaching 26.2 million (Longwoods International 2011). Travel for the purposes of leisure led the way as the primary motivation, accounting for 48% of overnight trips in 2011 (Longwoods International 2011).

Of particular relevance to this study, in 2010, 6% of all overnight trips were for the purpose of participating in ski tourism, compared to just 1% of overnight trips at the national level (Longwoods International 2011). Furthermore, in 2010 Colorado lead all states in the overnight ski travel market, accounting for 20% of all overnight ski trips in the country (Longwoods International 2011). Lastly, in the 2010/11 season, Colorado recorded the single most skier visits of all states, registering 12.3 million visits (NSAA 2011a). These factors influenced the selection of Colorado for case study ski areas from within the Rocky Mountain region.

Direct travel spending in 2010 was recorded at $14.6 billion, an increase of 5.1% over 2009, and supported 136,900 jobs generating an additional $3.9 billion in statewide earnings (Dean Runyan Associates 2011). Furthermore, in 2010 travel and tourism accrued $750 million in tax revenues, a figure that does not account for relative increases in property taxes at destinations (Dean Runyan Associates 2011). The tourism industry has sustained growth throughout the last 15 years, helping to maintain its importance as an economic sector; "since 1996, visitor-generated spending has increased at an average annual rate of 3.5%, earnings by 2.7%, and local and state tax revenues by 3.7% and 2.5%, respectively." (Dean Runyan Associates 2011).

Figure 2.3 displays the regions within Colorado referenced in the following paragraph, including where the case study ski areas are located. When examining its impact on a regional basis the Denver Metropolis area accounted for just under half (45%) of all overnight spending (Dean Runyan Associates 2011). For the Mountain Resort region, overnight spending accounted for 25% of the state's tourism earnings, however, these earnings are relatively more important, in relation to the size of the total economy in this region (Dean Runyan Associates 2011). Income generated through the travel and tourism industry accounted for 11.9% of all earnings in this region, a figure that equates to $921 million earned in 2010 (Dean Runyan Associates 2011).

Figure 2.3: Map of Colorado with Case Study Ski Areas



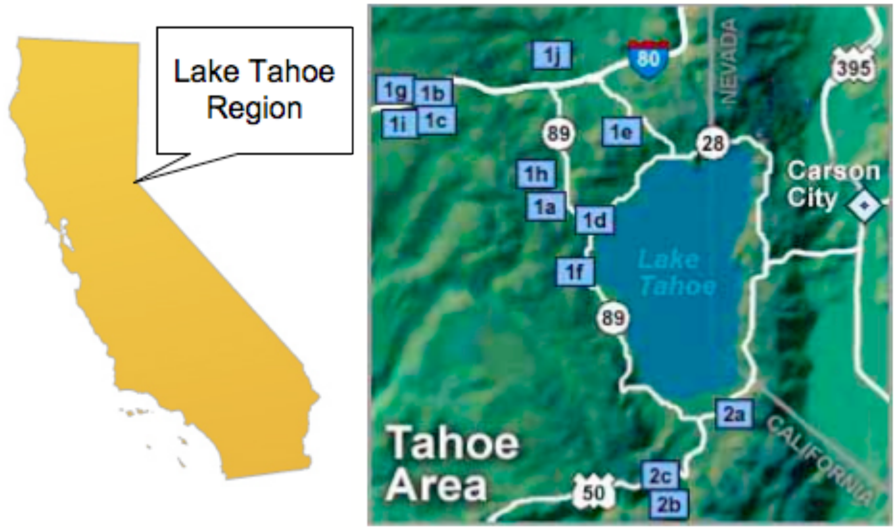
Source: Dean Runyan Associates (2011)
Note: Shading distinguishes major tourism regions within Colorado

California

California is located along the southern Pacific coast of the United Sates, and is home to nearly 37.7 million people, encompassing an area of 411,045 square kilometres, making it the 3rd largest state by land mass in the country (California Tourism 2012). Due to its size, diversity in landscape and cultural ethnicities the tourism potential for this state is touted as being unmatched by any other in the country California Tourism 2012). Figure 2.4 provides a map of California, indicating the major ski areas.

In 2011, tourists spent \$102.3 billion in California, an increase of 7.6% from the previous year (California Tourism 2012a). This spending supported 893,000 jobs, amassing an additional \$30.4 billion in income generated (California Tourism 2012b). Additionally, 4.4% of all employment in the state is directly supported by tourism (California Tourism 2012b). The tourism industry further contributed to the state economy through \$2.3 billion in local taxes as well as \$4 billion in states taxes (California Tourism 2012a). Tourist spending outperforms four of the state's top product exports, including aircraft, non-industrial diamonds and technology devices (California Tourism 2012b).

Figure 2.4: Map of California with Ski Areas



Source: Google.com, skitown.com (2012)

Note: Numbers at right denote ski area; 1h is Squaw Valley

Winter Alpine Tourism

Global Ski Industry

Globally, the ski industry is one of the most prevalent mountain tourism attractions with estimated global direct revenues at $9 billion annually in the mid-2000s (Scott & McBoyle 2007). This figure was reached through the aggregation of several regional studies on the ski industry; the American ski industry generated $3 billion (USD) in revenue (2003), western European ski areas generated revenues in excess of 3 billion (USD) (2002), Japan had annual revenues of $1.4 billion (USD) (2002), Canada was estimated as generating annual revenues of $680 million (USD) (2003), Australia's industry was valued at $94 million (USD) (2000) (Scott & McBoyle 2007). While providing a glimpse into the economic importance of ski tourism, this approach likely undervalues the industry considerably. For instance, Scott and McBoyle's (2007) assessment does not include indirect and induced revenues, incomes earned through employment in the ski industry as well as local and federal taxes accrued. This estimate also uses figures from as long as a decade ago and does not comprehensively include all ski regions.

The diversity of this industry and the way it is measured - or as often, not measured - makes it very difficult to conduct a comprehensive assessment of the industry's worth (Scott & McBoyle 2007). The composition of the ski tourism industry varies as drastically as its location; business models common to this industry range from multinational conglomerates (Vail Resorts, Inc.) which own and operate multiple international ski destinations, to state/provincially and single family run ski areas (Scott & McBoyle 2007). It also includes a multitude of auxiliary businesses such as instructors, hotels and restaurants, equipment sales and repairs, the latter of which do not necessarily need to be located in close proximity to a ski area (Scott & McBoyle 2007). Accounting for this diversity makes a comprehensive accurate appraisal of the economic value of this industry incredibly challenging. Thus, if all sources were considered within the current context it would be reasonable to assume the global ski industry is worth considerably more than Scott & McBoyle's (2007) estimate.

Vanat (2009) provides one of the only known assessments of global skier visits, estimated at ~400 million in 2009. Of this, the European Alps ski industry accounted for 42%, while ski areas in the Americas accounted for 22%, followed by Asia (19%), followed by the rest of Europe (10%), 'East' (4%), and 'Exotic' (3%) (Vanat 2009). When only including Austria, Canada, France, Italy, Japan, Switzerland and the U.S.A., there were approximately 2150 ski areas in 2009 (Vanat 2009). Emerging ski regions such as Eastern Europe, China and South Korea are anticipated to continue to expand into the future, these regions accounted for a 22% share in new lift investments (Vanat 2009).

State of U.S.A. Ski Industry

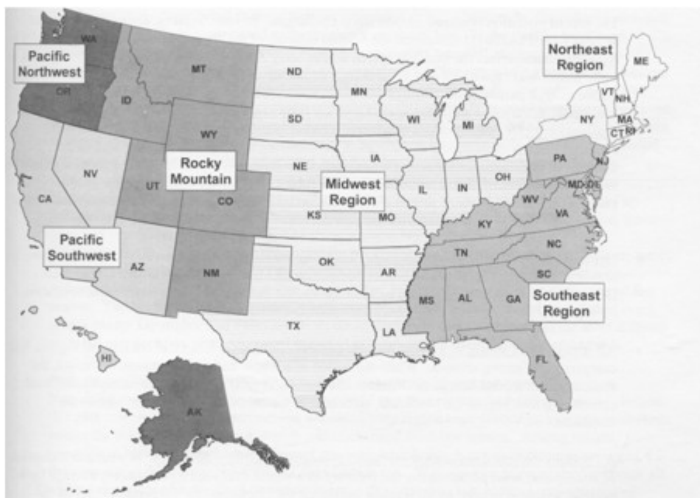
Regional Trends and Challenges

According the Colorado Ski Museum (2012), the roots of the American ski industry trace back to Scandinavian settlers in Northeastern states such as Maine and New Hampshire. Following World War II its popularity as a recreational past time increased exponentially (Colorado Ski Museum 2012). The NSAA, first established in 1962, is the trade association tasked with researching trends in the American ski industry to provide operators the information necessary for business decisions (NSAA 2011a).

The NSAA represents 321 alpine resorts throughout the USA, together these host more than 90% of annual skier visits in the country.

The NSAA separates the American ski industry into five regions: the Northeast, Southeast, Midwest, Rocky Mountain and Pacific West (the Pacific West becomes sub-divided into North and South regions in select reports if respondent levels dictate) (Figure 2.5) (NSAA 2010, NSAA 2011a, NSAA 2011b, NSAA 2011c). The NSAA provides data on various performance, demographic and climatic indicators, specified for each region. For this study, case studies were selected from the Rocky Mountain and Pacific West (Pacific South) regions were selected.

Figure 2.5: NSAA Regions



Source: NSAA (2011b)

The NSAA's Kottke National End of Season Survey (referred to hereafter as Kottke Report) is a report that examines and summarizes several key performance indicators of the national ski industry. The most important finding presented in the Kottke for the 2010/11 season is that visitation continued to rise, increasing by 1.3% over the 2009/10 season (NSAA 2011a). NSAA ski areas reached 60.54 million skier visits in 2010/11, exceeding the previous record of 60.5 million set in the pre-recession 2007/08 season (NSAA 2011a). Notably, the 2010/11 season was the seventh out of the last ten seasons to exceed 57 million skier visits nationally (NSAA 2011c). Looking at the 33-year lead up to the 2010/11 season, the Kottke Report stated that 2010/11 was nationally the best season on record. Of particular interest to this study is that the Rocky Mountain as well as Pacific regions had their second best seasons on record (NSAA 2011a).

Table 2.1 provides an overview of skier visits over the 2007/08-2010/11 timeframe. In examining this information, patterns of visitation between regions emerged that were important in justifying the selection of case studies in this research. The Rocky Mountain region accounted for the largest, while the Pacific West accounted for the third-largest, number of skier visits in 2010/11.

Table 2.1: NSAA Skier Visits 2007/08 - 2010/11

	2007/08	2008/09	2009/10	2010/11
Northeast	14260989	13730072	13410615	13886888
Southeast	5203953	5664058	6015832	5789279
Midwest	8098748	7247237	7718458	7811077
Rocky Mountain	21324224	19974486	20377710	20900328
Pacific West	11614545	10737987	12264385	12152925
Total	**60502459**	**57353840**	**59787000**	**60540497**

Source: NSAA 2011

Further supporting their selection, over the 1993/94-2010/11 period the Rocky Mountain and Pacific West regions were the only ones in the USA to not have a reduction in the number of ski operators (NSAA 2011a). The Rocky Mountain region increased its number of operators by 5.5% over this period, while the Pacific West region had annual fluctuations but as of 2010/11 registered the same number of operators (76) as in 1993/94 (NSAA 2011a). Furthermore, since the 1978/79 season annual visitation in the Rocky Mountain region grew more than any other region, increasing by over 5 million visits (NSAA 2011a). The Pacific West region had the second highest growth as annual visitation increased by approximately 2.5 million visits over the same time period (NSAA 2011a). Such figures assisted in selecting these two regions beyond the current gap in the literature.

The NSAA identified snowmaking as an indispensable part of the operations at most ski areas (NSAA 2011c). Nationally, 88% of ski areas are equipped with some level of snowmaking, in the case study regions, 89% (Rocky Mountain) and 80% (Pacific South) of ski areas are equipped (NSAA 2011c). However, these regions have the lowest proportion of skiable terrain equipped for snowmaking, at only 12% (Rocky Mountain) and 13% (Pacific South). The NSAA (2011c) also note that despite the Rocky Mountain and Pacific South regions' below average proportion of terrain equipped with snowmaking, these regions have above average absolute acres equipped with snowmaking. The Rocky Mountain has 219 acres equipped with snowmaking, while the Pacific South has 233 acres, these are exceeded only by the Northeast at 302 acres (NSAA 2011c). While these values vary year-to-year, 2010/11 findings presented in the Kottke are largely unchanged from recent years.

Demographic Trends and Challenges

Results from the NSAA's demographic analysis of the 2010/11 season indicate that skiers and snowboarders are continuing to recover from the 2008/09 economic recession; per capita daily spending resumed long-term trends by increasing in 2010/11, after dropping in the 2008/09 and 2009/10 seasons (NSAA 2011a). This is likely the result of the improved economy as average household incomes among participants also rose in 2010/11 (NSAA 2011b). It was found that ski and snowboard participants are likely to have a more affluent profile– related to annual household and disposable income - in comparison to the general American public (NSAA 2011b).

Similar to broad national trends, American ski tourism participants are aging; a disconcerting finding that will have important implications for the long-term success of the industry (NSAA 2011b). However, the NSAA (2011a) reports that loyalty amongst these older participants is responsible for "increasingly turning snow sports into a three generation activity" (pp. 3). The NSAA has initiated a program to increase participation among younger age cohorts, which has progressed with mixed success. While the following does suggest long-term trends, an encouraging statistic is that children's lessons rose by 2.9% with children's season passes increasing by 13.6% in 2010/11 (NSAA 2011b). However, new participants are more likely to participate at smaller, individually run ski resorts (NSAA 2011a, NSAA 2011b, Scott et. al. 2012b). These resorts have been repeatedly identified in the literature as more likely to be at risk from climate change since they typically possess a lower level of adaptive capacity (McBoyle & Wall 1992, Scott, Jones, Lemieux, McBoyle, Mills, Svenson & Wall 2002, Burki, Elsasser & Abegg 2003, Scott et. al. 2008b).

Economic Trends and Challenges

As outlined by the NSAA, trends over the 2006/07-2010/11 period show promising growth; "The long term growth in revenue and operating profit has been strong. Gross revenue has grown by 11.4 percent over the five-year period (with a compound annual growth rate of 2.2 percent per year) and operating profit has increased by 9.8 percent (compound annual growth rate of 1.9 percent per year)" (NSAA 2011c, ES-3). Despite a reduction in the 2010/11 season, national operating profit margin "remains within a typical historical range (24 to 26 percent)" (NSAA 2011c).

Pertinent to this study, the national average for total snowmaking related expenses was recorded at $489,000 per resort in the 2010/11 season, equating to 2.7% of total expenses nationwide, an increase of only 1% above 2009/10 (NSAA 2011c). Of note, in 2010/11 the Rocky Mountain's (1.7%) and Pacific West region's (Pacific South 1.6%, Pacific North 0.1%) proportionate costs for snowmaking were reduced relative to this national average. While these figures provide insight into snowmaking costs, they do not necessarily indicate long-term trends, as such these figures are provided as a frame of reference for national snowmaking costs. Long-term trends indicate that costs have risen over the ten-year period leading to the 2010/11 season (NSAA 2011a, 2011c). As snowmaking diffusion continues and ski areas increase the proportion of terrain equipped with snowmaking longer term trends are expected to continue. However, increases in snowmaking equipment efficiency may serve to balance the increased cost from expansion.

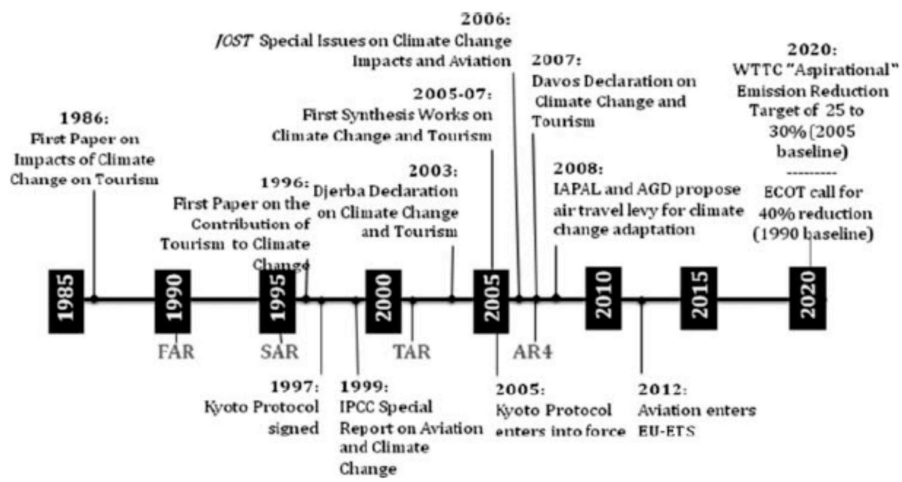
Tourism and Climate Change

Emergence of the Climate Change Issue Within Tourism

Climate change became a prominent global issue in the late 1980s and early 1990s, however, it did not become widely discussed in the travel and tourism literature until a decade later. Scott, Wall and McBoyle (2005) state that this body of literature grew intermittently throughout the latter portion of the 20th century (1980s, 1990s), gaining momentum in the early 21st century as the number of publications greatly increased (Figure 2.6). Typical early publications were regional assessments of potential impacts of a changing climate on recreation and tourism. For example, McBoyle and Wall (1987) examined downhill skiing in the Laurentian Mountains while Wall et. al. (1986) focused on camping in Ontario, together these found that a changing climate would pose both risks and opportunities (McBoyle et. al. 1986, 1987; Wall et. al. 1986).

Following these publications the climate change and tourism discourse greatly expanded throughout the 2000s. The contribution of multi-disciplinary research resulted in "doubling the number of publications that examine the two-way interactions of tourism and climate change between 1996-2000 and 2001-2005" (Scott et. al. 2012b, pp. 92). This multi-disciplinary approach is considered both a strength and weakness; it generates "new ideas and research techniques", however, the "differing disciplinary perspectives on the validity of assumptions and findings" presents challenges (Scott et. al. 2012a, pp. 214). Following 2005, the tourism and climate change literature continued to grow focusing on the range of potential impacts to various sub-sectors and destinations. The need to further study the inter-linkages between tourism and projected climate change remains a primary component of the academic literature (Scott et. al. 2012b).

Figure 2.6: Timeline of Climate Change and Tourism Issue



Source: Scott & Becken (2010)

Tourism's inclusion in the IPCC's assessment reports was also delayed relative to other industries (Scott et. al. 2005, Scott et. al. 2012b). It was not considered in the First Assessment Report (FAR), however, it did receive some attention in the IPCC's Second Assessment Report (SAR) though this did not include any consideration of tourism's contributions to projected climate change (Scott et. al. 2012b).

Prior to AR4, the UNWTO held the First International Conference on Climate Change and Tourism in Derjba, Tunisia, 2003, focusing on how the tourism industry must adapt to and mitigate further climate change (UNWTO 2003). This lead to the

Derjba Declaration on Climate Change and Tourism, a detailed framework for future works into adaptation and mitigation research and policy-making (UNWTO 2003, Gossling 2011, Scott et. al. 2012b). Following this declaration, the UNWTO held the Second International Conference on Climate Change and Tourism in Davos, Switzerland, 2007, which led to the Davos Declaration on Climate Change and Tourism – (UNWTO & UNEP 2008). The foremost outcome of the Davos Declaration was the substance it added to the Derjba Declaration, providing specific objectives and direction for tourism and its role within the climate change spectrum.

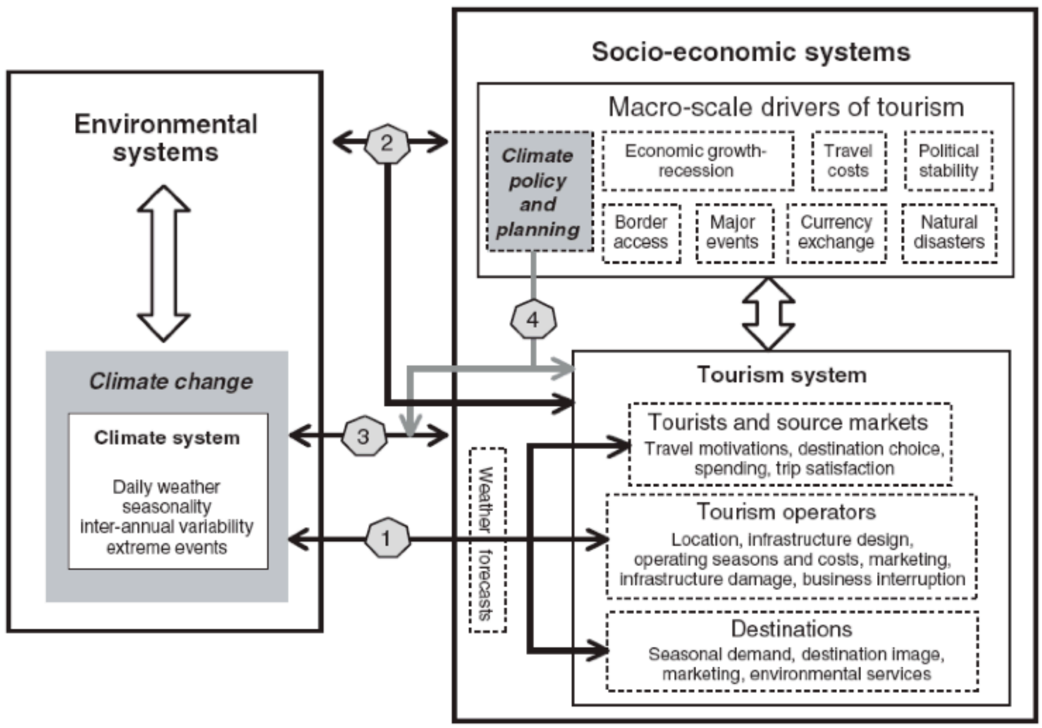
Accompanied with the Davos Declaration, the *Climate Change and Tourism: Responding to Global Challenges* report provided a comprehensive statement of knowledge on the tourism and climate change issue. It provided an assessment of the global issue providing case specific examples of vulnerabilities, adaptation strategies and mitigation efforts (Scott et. al. 2008b). In this report climate change was identified as the greatest challenge to sustainable tourism in the 21st century (Scott et. al. 2008b).

There has been a notable increase in the response by tourism stakeholders in addressing climate change since the turn of the century. Scott et. al. (2012b) cite the "policy momentum generated by the release of the IPCC's Third Assessment Report [TAR] (in 2001) and the Kyoto Protocol entering into force as an international treaty (in 2005)" as essential to the involvement of international tourism stakeholders in the issue. Following AR4, the first "coordinated response of the tourism industry became visible", evident through the WTTC's (2009) *Leading the Challenge* report, the first ever industry position paper to set emission reductions targets (WTTC 2009, Scott et al. 2012, pp. 93).

Tourism Vulnerability to Climate Change

The tourism industry has been repeatedly identified as highly susceptible to the adverse impacts of climate change. Scott et. al. (2012b) identify four mechanisms through which climate change could impact tourism operations; 1) direct impacts from climate change denote the restriction of an activity as the direct result of climate change, 2) indirect impacts from environmental change are those associated to losses in auxiliary resources such as biodiversity and water availability or may be due to increased frequency and severity of extreme events, 3) indirect impacts from societal change will result from reduced discretionary incomes due to climate change, and 4) induced impacts from climate change mitigation and adaptation actions occur due to the restriction of tourist's mobility or activity accessibility. Figure 2.7 outlines this conceptual framework. While it is possible to contend the ski industry is at risk from all four types of impacts, it is most likely to experience direct impacts to the largest degree through a reduction in season length.

Figure 2.7: Conceptual Framework for Tourism and Climate Change



Source: Scott, Hall & Gossling (2012b)

Beyond these four types of impacts, projected impacts in the tourism literature vary according to their inclusion of adaptation strategies. Scott et. al. (2012b) state that projections of potential impacts to tourism from climate change exclusive of adaptive responses are best considered "potential climate change impacts" while those inclusive of adaptive responses can be considered "residual climate change impacts" (pp. 189). Residual impacts provide a more accurate assessment of a destination's vulnerability to climate change since they account for adaptive capacity, and better assess the level of change most likely to occur should operators prepare themselves for change.

At the destination or regional level, the determination of 'winners and losers' from climate change will be equally dependent upon the level of change experienced as well as the decisions of operators and those of their competitors, resulting in a redistribution of market share (Scott et. al. 2008b, Scott et. al. 2012b). When examining this concept at the global scale, 'winners & losers' will be more greatly determined through the level of change experienced as well as due to emissions mitigation policy. Impacts will again result from tourists altering their travel timing and destination selection preferences to accommodate or seek out certain climatic conditions or activities. Beyond this, emissions mitigation policies could restrict the viability of international travel to countries such as Australia and New Zealand, along with many Small Island Developing States (SIDS), due to their reliance on air transport to bring tourists in (Scott et. al. 2008b, Scott et. al. 2012b). Consequently, these countries are the primary champions for restricting the creation of aviation mitigation policies, and alternatively focusing efforts on other emission sources (Scott et. al. 2008b).

It is important to reinforce the sentiment that "regardless of the nature and magnitude of climate change impacts, all tourism businesses and destinations will need to adapt to climate change" (Scott et. al. 2008b, pp 30). Whether a destination or region is anticipated to be adversely or beneficially impacted, proper planning will be necessary to best cope with potential changes.

Tourism Industry Emissions & Mitigation

In addition to being identified as vulnerable to climate change, the tourism industry contributes to global GHG emissions and change. Scott et. al. (2008a) provide an estimate of CO_2 emissions from the transportation, accommodation and activities sub-sectors within tourism. When combining international and domestic tourism, tourism emissions in 2005 were estimated at 1,302 Mt of CO_2, accounting for 3.9%-6.0%, with a best estimate of 5%, of total CO_2 emissions (Scott et. al. 2008b). The World Economic Forum (WEF) (2009) provided another assessment of tourism's contribution to global CO_2 emissions, estimated at 1476 Mt in 2005, it is 13% above that of Scott et. al. (2008a). This estimate was again refined as tourism contributing 5.2%-12.5% of global radiative forcing (Scott, Peeters & Gossling 2010, Scott et. al. 2012b). Table 2.2, adapted from Scott et. al. (2008a), outlines three sub-sectors of the tourism industry's emissions in 2005.

The source of emissions varies according to travel patterns and preferences. Scott et. al. (2008a) note that emissions can vary from "a few kilograms of CO_2 up to 9 t CO_2 for long distance, cruise-based journeys" (pp. 34). Regardless, the transportation sector accounts for the greatest proportion of tourism's emissions, responsible for approximately 75% (Scott et. al. 2008b). Interestingly, the aviation industry accounts for the single largest proportion of emissions within transportation at 40%, despite only 17% of all trips involving air travel (Scott et. al. 2008b).

As cited above, the WTTC's (2009) position paper on climate change was the first of its kinds to set emissions reduction targets for the global tourism industry. These were assessed at emissions being reduced by 25% by 2020 and 35% by 2035, both relative to 2005 emissions (1,302 Mt CO_2) (WTTC 2009). The suite of options for reducing emissions in the tourism industry is substantial, and includes the potential to mitigate emissions through technical, economic and socio-cultural actions (Gossling 2012). Most mitigation efforts can be categorized into either: energy reduction, efficiency improvements, increasing renewable energy use and carbon sinks (Scott et. al. 2012b). These are possible between tourism sub-sectors, providers and tourist themselves. Scott et. al. (2012b) state that "systemic strategies to reduce emissions from tourism need to consider the development of average distance traveled, the frequency of travel per individual, as well as the energy intensity of the travel modes used" (pp. 114). It is often stressed that the transportation sub-sector, and specifically aviation, should receive the greatest attention due to its proportional emissions, the likelihood of emissions growth in this sub-sector, as well as the potential impact of international GHG mitigation policies (Scott et. al. 2008b, Scott et. al. 2012b).

Table 2.2: Global Tourism Sector CO_2 Emissions (2005)

Tourism Emissions	CO_2	
Sector	Mt	Tourism (%)
Air Transport	515	40
Car	420	32
Other Transport	45	3
Accommodation	274	21
Other Activities	48	4
Total Tourism	1,302	100
Total World	26,400	-
Share of Tourism in Total World (%)	4.9	-

Source: Scott et. al. (2008)

Adaptive Capacity, Adaptation Strategies and Preparedness

Adaptive capacity is one of the main determinants of becoming either a 'winner' or 'loser' from climate change (Scott et. al. 2008b). In the tourism context, the level of adaptive capacity varies between tourists, tourism operators and destinations (Scott et. al. 2008b). Tourists are considered to have the highest level of adaptive capacity since they may select alternative destinations or alter the timing of their trips (Scott & Jones 2006, Scott et. al. 2008b). Tour operators and suppliers are assessed as having the second highest level of adaptive capacity as they will retain the ability to cater their services to tourist's demands (Scott et. al. 2008b). Destinations such as resort complexes have the least adaptive capacity due to their fixed nature (Scott. et. al. 2008).

To date, adaptation strategies to climate variability are in place throughout various destinations and tourism sectors. Table 2.3 provides select examples of tourism adaptation strategies to climate change currently in place (Scott et. al. 2008a). Due to the clear connection with climate and the environment, tourism operators already engage in climate adaptation practices regardless if these are intended as adaptations to climate variability or change (Scott et. al. 2008b).

In general, tourism industry operators and stakeholders are regarded as unprepared for the adverse consequences of climate change (Scott et. al. 2012a). Industry representatives recognize the significance of projected climate change, however, many were found to be overly optimistic regarding their ability to successfully adapt (Scott et. al. 2012a). Of relevance to this work, ski area managers, while acknowledging the threat posed by climate change, are overly optimistic in the ability of snowmaking to absorb potential impacts from climate change (Wolfsegger, Gossling & Scott 2008, Scott et. al. 2012b).

Table 2.3: Examples of Tourism Industry Adaptation Strategies in Place

Location	Climate Change Impact	Adaptation Strategy
Tobago	Water shortages due to increased Drought	Retrofit buildings with rainwater collection systems, converting toilets to saltwater, desalination machinery, water conversation practices, limited use of pools
Caribbean Region	Seasonality Changes, increased frequency of extreme events	Altered marketing and advertising campaigns to promote visitation during off-season periods, 'Blue Chip Hurricane Gaurantee' program - provides visitors with replacement stay if Hurricane occurs
Fiji	Coastal erosion and Sea-level rise	Construction of 'sea-walls' to decrease erosion, new building practices and regulations

Source: Scott et. al. (2008)

Shifts in Tourism Resources and Flows

There is an anticipated change in climatic and environmental resources for tourism and subsequently flows of tourists from projected climate change (Scott, Hall & Gossling 2012a). Studies that examine potential changes to tourism's climate resources typically employ a "Tourism Climate Index" to assess relevant weather and climate variables in relation to tourist's destination selection patterns (Scott et. al. 2012a, pp. 216). Projected changes from these studies follow consistent geographic and temporal patterns, reaching the general consensus that in the future it is likely that "conditions ideal for tourism activity" will: expand into higher latitudes, improve during summer seasons while being degraded in winter season in mountain environments, become degraded in equatorial zones (Scott et. al. 2012a, pp 216).

Shifts in tourists' demand and destination selection patterns are largely anticipated to follow projections for the redistribution of climate resources for tourism as the pertinent push-pull factors change (Hamilton, Maddison & Tol 2005, Berrittella, Bigano, Roson & Tol 2006, Bigano, Hamilton & Tol 2007, Hamilton & Tol 2007, Scott et. al. 2012a). Accordingly, countries such as Canada, the U.K., Russia, Australia, as well as Scandinavian countries are projected to benefit the most (Hamilton & Tol 2007, Bigano et. al. 2007, Scott et. al. 2012a). At the global scale this is anticipated to have a significant impact on international tourist arrivals since the countries projected to benefit most are also where most tourists typically originate (UNWTO 2012). Consequently, a reduction in international tourist arrivals and increase in domestic travel is likely to occur over the 21st century (Scott et. al. 2012a). However, this reduction to international arrivals may be stymied from increased arrivals of tourists originating in tropical and sub-tropical countries (Scott et. al. 2012a).

Climate Change and the Ski Industry

Ski Industry Environmental Stewardship & Emissions Mitigation

Despite its vulnerability to climate change, the ski industry generates a considerable amount of GHG emissions largely due to its energy intensive operations (NSAA 2010, NSAA 2011a, NSAA 2011c, Wortman 2012). Large portions of its emissions are incurred through participants' travel to and from destinations (Scott & McBoyle 2007). To date, no known assessments have attempted to quantify emissions from this sub-sector of the tourism industry.

Collectively, American ski areas are working to improve their impact on natural systems through the *Keep Winters Cool* campaign, the *Sustainable Slopes Program*, and the *Protect Our Winters* non-profit organization (NSAA 2005, Scott & McBoyle 2007, protectourwinters.com 2011, Wortman 2012). Led by different sectors and stakeholders in the industry, these programs work in unison to mitigate GHG emissions while also increasing ski areas' overall environmental stewardship. To date, the progress and accomplishments of these programs vary. While individual resorts have implemented policies that reduce their carbon footprint any industry-wide measurable reductions in CO_2 emissions are unknown (NSAA 2012).

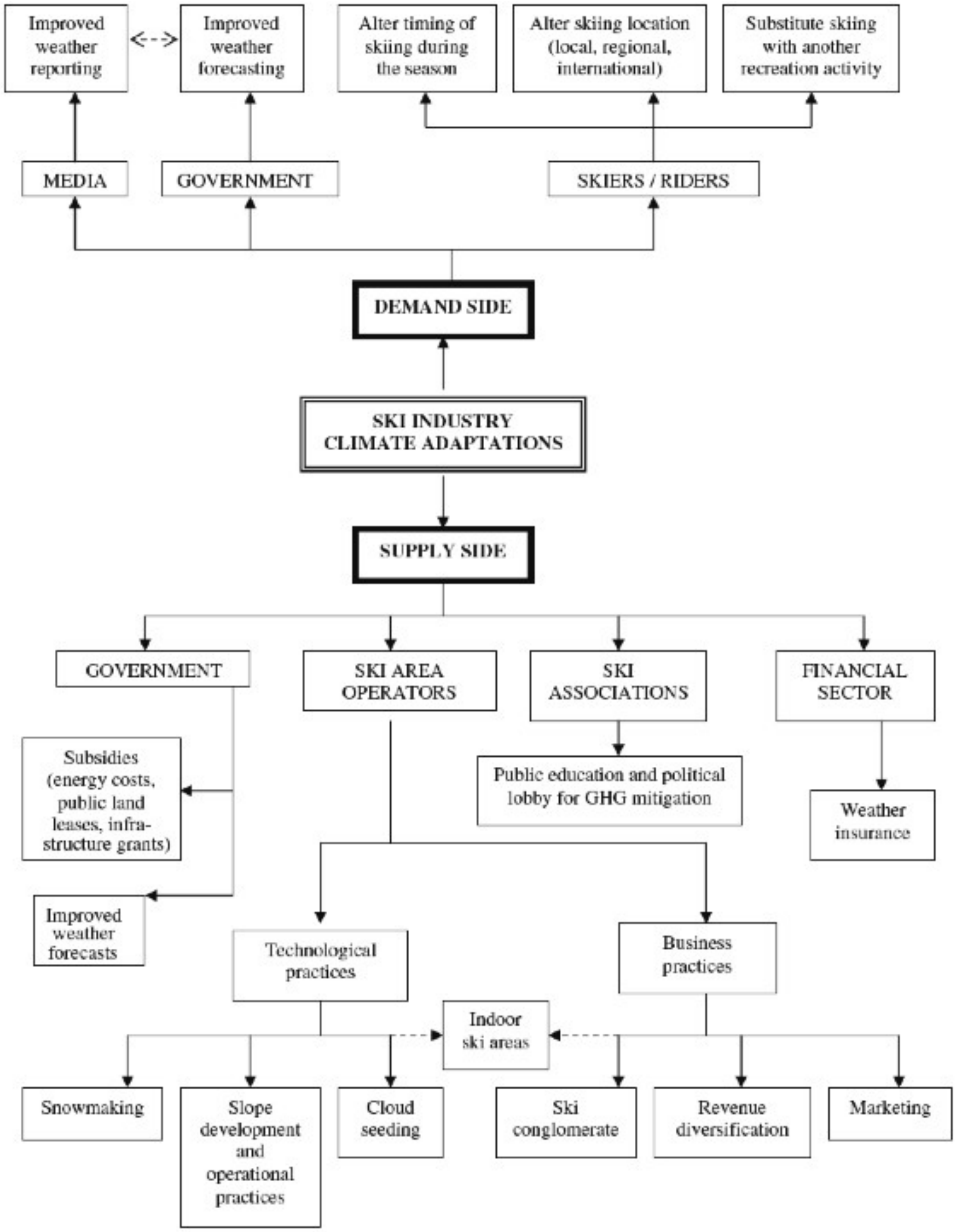
Ski Industry Adaptation

The ski industry has a suite of adaptation options at its disposal for combating the adverse impacts from projected climate change. Scott & McBoyle (2007) outline these options, differentiating between supply side and demand side options (Figure 2.8). Similar to the general profile of adaptation options for the tourism industry, demand side options in the ski industry include tourists altering the timing or location of their participation, or substituting skiing with another activity (Scott & McBoyle 2007). Supply side adaptation options are more abundant and can be undertaken by government organizations, ski area operators, ski industry associations as well as financial institutions (Scott & McBoyle 2007).

Broadly, ski area operators' adaptation options can be segregated into technical and business options (Scott & McBoyle 2007). Technical options include those taken to improve the ski product while business options involve diversifying revenues and stakeholder groups and improving advertising campaigns to better market a destination (Scott & McBoyle 2007). The suite of technical options for ski operators includes snowmaking, improved slope development and grooming, and cloud seeding (Scott & McBoyle 2007). Ski operators can exert some control over the demand-side options listed above through effective marketing campaigns aimed at sustaining visitation (Scott & McBoyle 2007).

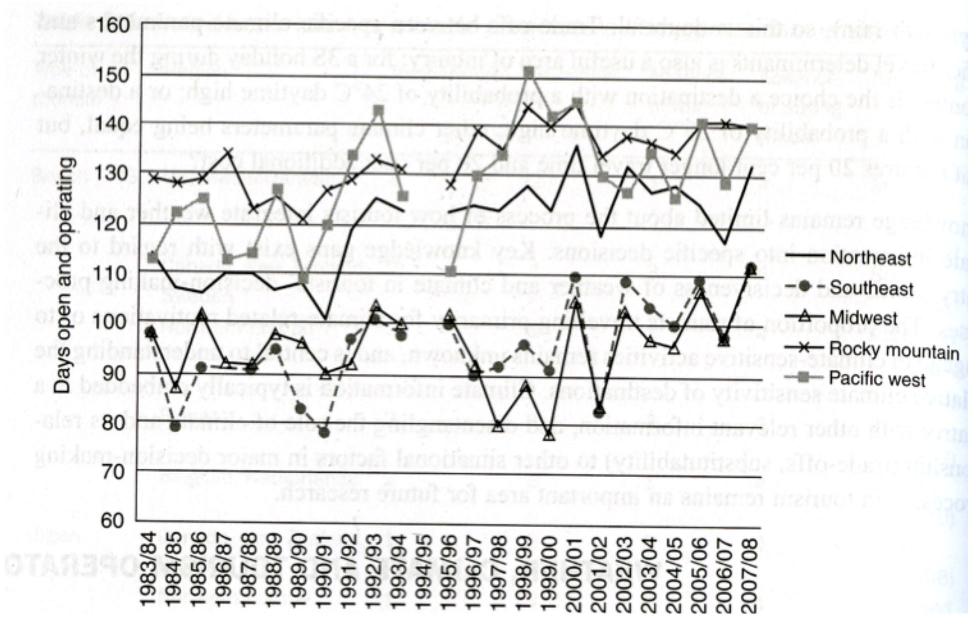
The North American ski industry experiences natural fluctuations in season length according to annual changes in weather conditions (Figure 2.9) (Scott et. al. 2012b). Snowmaking was initially developed to combat interseasonal variability in ski season length, and is now considered the most prevalent climate adaptation option employed by the ski industry (Scott et. al. 2008b, Steiger 2010, Scott et. al. 2012b). Figure 2.10 depicts its diffusion in the U.S.A. in recent years. However, as noted above, many ski area managers are overly optimistic, and reliant, on the efficacy of snowmaking in mitigating adverse impacts from climate change (Scott et. al. 2012b). Depending on the level of change experienced as well as external limitations to its use - such as economic and environmental restrictions - its applicability will be limited for certain ski regions (Scott et. al. 2012b).

Figure 2.8: Ski Industry Adaptation Options



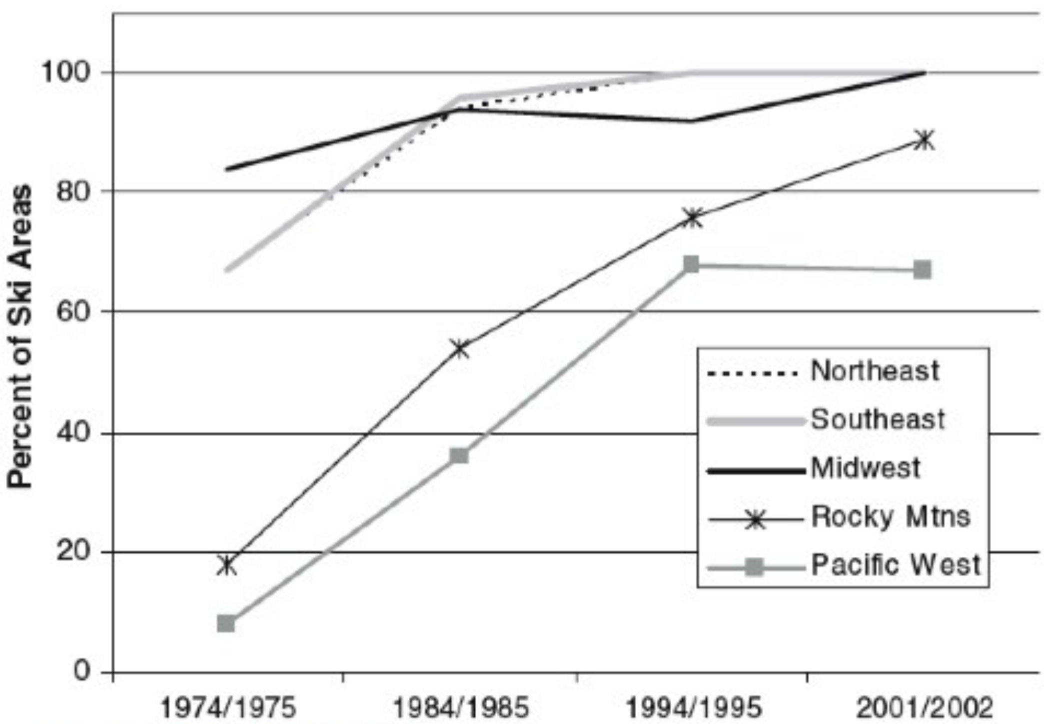
Source: Scott & McBoyle (2007)

Figure 2.9: USA Ski Season Length Variability



Source: Scott et. al. 2012

Figure 2.10: USA Snowmaking Diffusion



Source: Scott & McBoyle (2007)

The importance of this technology is displayed by Scott, McBoyle and Minogue (2006) who found that season length under natural conditions alone, using 30cm of snowpack as the operational threshold, at Brighton, Michigan was six days, however, average season length for the region, from 1983/84-2001/02 was 93 days (Scott et. al. 2006). Despite this display of efficacy, snowmaking will not mitigate all adverse impacts associated with continued climate change.

This is best displayed through the projected reductions to ski season length despite 100% snowmaking coverage in the select number of studies that have included snowmaking (Scott et. al. 2003, Scott et. al. 2006, Scott et. al. 2008b, Steiger 2010). Beyond these studies, others have attempted to study the limits of snowmaking in warmer futures and found that snowmaking operations will likely be jeopardized from climate change, further reducing their efficacy (North America: Bark et. al. 2010, Australia: Pickering & Buckley 2010).

Bark et. al. (2010) examined the use of snowmaking at ski areas in Arizona to determine when, under projected climate change, the technological limits would be exceeded. Assuming snowmaking was possible at -5°C or colder, with a preferred temperature of -7°C or colder, the number of potential snowmaking days by 2050s will become jeopardized in the shoulder seasons and become increasingly jeopardized throughout the core season by 2080s (Bark et. al. 2010). This is best evidenced by the authors' suggestion that by the 2050s to 2080s this region could lose its Thanksgiving ski period (late November) because of an insufficient number of consecutive days with natural snowfall or where snowmaking is possible (Bark et. al. 2010).

The financial investments in infrastructure and energy, combined with projections of reduced water availability, are an additional limitation to the future use of snowmaking as an adaptation strategy (Scott et. al. 2006, Bark. et. al. 2010, Pickering & Buckley 2010). Bark et. al. (2010) found that together the increased requirements for these resources is likely to inhibit its use as a climate change adaptation strategy by 2050 more than technological limitations; additional revenues from sustained ski season length may not offset such expenses. Pickering and Buckley (2010) drew similar conclusions in examining the potential of snowmaking as an adaptation strategy for Australian ski resorts. While, Vanham, Flieschhacker and Rauch (2009), who consider the snowmaking strategy for the Kitzbuhel region in Austria, and state that increased water demand for snowmaking will stress resources, requiring the establishment of reservoirs for this use reducing its efficacy in sustaining this industry.

The ski areas examined in this study face these risks due to their proportional amount of terrain currently equipped with snowmaking, but also because the states in which they are located have had their freshwater resources identified as at risk from climate change (Wilderness Society 2009a, 2009b, NSAA 2011a).

Previous Ski Industry and Climate Change Assessments

Despite the tourism and climate change literature developing slowly in relation to other economic sectors, research on climate change and the ski industry has been amply conducted (Scott. et. al. 2008). Following the initial work by McBoyle et. al. (1986, 1987) winter alpine tourism has been repeatedly identified as one of the most vulnerable sectors of the tourism industry (Scott et. al. 2008a). Previous assessments can be categorized into either supply or demand-side assessments.

Demand-Side Ski Assessments

Studies that seek to assess the demand implications for ski tourism from climate change have been limited to select ski tourism regions -Australia, Austria, Switzerland, New Zealand, and America – and present scenarios of snow and weather conditions, asking respondents how they may alter their ski behaviour if such conditions were to arise (Koenig 1998, Behringer, Burki & Fuhrer 2000, Unbehaun Probst & Haider 2008, Prince 2010, Pickering, Castley & Buckley 2010, Vivian 2011, Scott et. al. 2012b, Scott et. al. 2012a). Readers are referred to Scott et. al. (2012b) for a complete account of these studies, only those most pertinent to this study are included below.

Koenig (1998) conducted the first demand-side assessment of potential changes to ski tourism in Australia by asking respondents how they would alter ski participation if snow conditions were to be depleted for the next consecutive five seasons. Their results indicate that 25% would continue to ski at the same rate in Australia, 31% would ski less often but still in Australia, 38% would substitute destinations and ski abroad, while 6% would quit skiing altogether (Koenig 1998). When this study was repeated a decade later 90% of skiers (+15%) indicated they would participate less often in Australia (Pickering et. al. 2010). This follow-up study is important as the contrasts between findings provide insight into the public's perception of climate change and its impacts (Scott et. al. 2012b).

Scott et. al. (2012b) note that these assessments are limited by the inherent subjectivity of their surveys. Differences between respondent's interpretations of scenarios allows for considerable uncertainty in how participants' behaviours may actually change (Scott et. al. 2012b). Accordingly, Vivian (2011) sought to better account for this in the Northeast USA ski region. When presented with the seasonal characteristics representative of an analogue season (2001/02), the majority of respondents (87%), would not alter their frequency, however, 23% would travel further within the New England, while 9% would leave the region to satisfy demand (Vivian 2011, Scott et. al. 2012b). When presented with the seasonal characteristics representative of a 2050s future high emission scenario, again the majority indicated they would not alter their frequency (84%), however, in this scenario an increased proportion of respondents (30%) would travel further within New England while a similar proportion (11%) would leave to satisfy demand (Vivian 2011, Scott et. al. 2012b)

Dawson, Havitz and Scott (2011) found that behavioural adaptations to climate change vary between participant segments. Of note, ski enthusiasts are likely to increase visitation intensity over a shortened season, while those who identified a high level of loyalty to certain ski areas and/or those with property or capital investments located nearby were less likely to substitute destinations (Dawson et. al. 2011). The combined results of Vivian (2011) and Dawson et. al. (2011) are germane to this work as western North American ski destinations have been identified in the literature as likely to benefit from ski tourists altering their demand patterns as a result of climate change (Zimmerman et. al. 2006, Scott et. al. 2012b).

Climate change analogue assessments (further discussed below) also provide insight into demand-side adaptations to climate change. Examining the climate change analogue seasons of 1998/99 and 2001/02, Dawson, Scott and McBoyle (2009) found that in the Northeast ski region demand decreased. In these seasons ski areas in the Northeast U.S.A. drew 11% (1998/99) and 12% (2001/02) fewer visitors than the approximate 13.5 million visits during the average years (Dawson et. al. 2009).

Supply-Side Ski Assessments

To date, supply-side assessments have identified vulnerabilities from climate change for ski tourism in western Europe (Germany, Italy, Austria, France, Spain, Switzerland), Canada (Ontario, Quebec, Alberta) the United States (Vermont, New Hampshire, Michigan) as well as Australia (Scott et. al. 2008a). In addition to these locations other areas examined include Scotland, Sweden and Japan (Scott & McBoyle 2007). Readers are again referred to Scott et. al. (2012b) for a comprehensive review of supply-side studies, only those pertinent to this work are summarized below. Supply-side assessments have largely employed two methodologies; climate change analogues and ski operations modeling (Scott et. al. 2012a).

Climate Change Analogue Assessments

Climate change analogue studies employ a methodology in which performance indicators during a climatically atypical year are judged against the same indicators under climatically average years (Scott 2005, Dawson et. al. 2009, Steiger 2011, Scott et. al. 2012b, Scott et. al. 2012a). Weather conditions in the atypical year generally constitute record values and are analogous for future climate change scenarios (Scott et. al. 2012a). In the tourism literature this is considered a beneficial approach to future planning as it allows the ability to consider both supply and demand-side impacts from potential climate change (Steiger 2011, Scott et. al. 2012a). However, an important limitation to these studies is the assumption that behavioural patterns in individual analogue seasons are representative of prolonged scenarios of change (Scott et. al. 2012b).

Dawson et. al. (2009) performed a climate change analogue analysis for the New England ski tourism industry. The authors used the 2001/02 and 1998/99 analogue seasons to compare select performance indicators for the climatically average seasons of 2000/01 and 2004/05 (Dawson et. al. 2009, pp. 3). Their results indicate that in comparison to the 2000/01 and 2004/05 seasons, average season length in analogue years was reduced by 3.4% (1998/99) and 10.9% (2001/02) (Dawson et. al. 2009).

As a result of reduced natural snowfall (-40%), snowmaking hours increased by 76% (1998/99) and 11% (2001/02), while the proportion of energy used for snowmaking increased by 37% (1998/99) and 21% (2001/02) in the analogue years (Dawson et. al. 2009). Altogether, these factors negatively impacted ski areas' financial bottom line in the analogue seasons (Dawson et. al. 2009). The high emissions climate change analogue season (2001/02) had operating profit reductions of 33%, however, the mid-emissions climate change analogue season (1998/99) only recorded reductions to profits at small (-28%) and extra-large (-12%) sized ski areas (Dawson et. al. 2009). Across the ski region, the Northeast was able to maintain operating profit in the 1998/99 season, causing the authors to suggest that ski area operations can successfully adapt to warmer climate conditions (Dawson et. al. 2009).

Steiger (2011) followed a similar methodology to Dawson et. al. (2009), using the record warm 2006/07 season in Tyrol as the climate change analogue (Steiger 2011). Consistently in the analogue season, ski areas with greater snowmaking coverage and those at higher mean altitudes were less likely to be adversely impacted (Steiger 2011). When comparing two large-sized, low-elevation ski areas, ski area A (with 47% snowmaking coverage) experienced total losses to ski lift transport of 61%, while ski area B (with snowmaking coverage at 88%) experienced total losses of only 4% (Steiger 2011). Likewise, when examining two mid-sized mid-altitude ski areas, ski area C (with no snowmaking) recorded losses to lift transports of 45%, while its counterpart ski area D (with 61% snowmaking coverage) profited with ski lift transports increasing by 11% (Steiger 2011).

Ski Operations Modeling Assessments

Ski operations modeling is the second and most common methodology in assessing the vulnerability of ski tourism to climate change with multiple methodologies present in the literature (Scott et. al. 2012b). Studies that attempt to model ski operations have considered many prominent global ski regions with projections varying in severity of impacts and inclusion of adaptation strategies.

A common methodology applied in western European studies has been to assess the line of 'natural snow reliability' (natural snow line); a term used to determine if enough snow is consistently present for ski operations to be successful at a given altitude or location (Koenig & Abegg 1997; Steiger 2010). This assessment incorporates the '100-day rule' which states that an area must have sufficient snow cover, identified as 30cm or greater, for at least 100 days per season, seven out of ten seasons, in order to be profitable (Koenig & Abegg 1997; Steiger 2010). It is a working guideline for successful operations that has been confirmed by ski area operators (Scott et. al. 2003).

Koenig and Abegg (1997) conducted a regional assessment of climate change on the Swiss ski industry, examining the natural snow line they determined that under a warming scenario of 2°C only 63% of ski areas would remain snow reliable, compared to 85% of ski areas under average climate conditions at the time of writing (Koenig & Abegg 1997). This methodology was repeated by Abegg, Agrawala, Crick and de Montfalcon (2007) for all Organization for Economic Co-operation Development (OECD) nations and found that only 75, 61 and 30% of ski areas would remain snow reliable under 1, 2 and 4°C warming scenarios, respectively (Abegg et. al. 2007). This compares to 91% of the 666 ski areas analyzed being considered snow reliable at the time (Abegg et. al. 2007). Snowmaking was not considered in this study.

Within North America, early supply-side assessments focused on the Great Lakes Region and New England, predicting similarly unfavourable conditions. The earliest research predicted 30 to 40% reductions in season length for ski areas north of Lake Superior, similar impacts were predicted for American Great Lakes ski areas with reductions ranging from 30 to 100% (McBoyle et. al. 1986, Lipski & McBoyle 1991, Scott et. al. 2006). The limitations of these early studies, namely the omission of adaptive strategies, irrelevant timeframes assessed and minimum snow depth required for ski operations, lead to a second-generation of ski industry climate change assessments (Scott et. al. 2008a).

The omission of snowmaking as an adaptation strategy to projected climate change remains a critical limitation to assessments (Scott & McBoyle 2007, Scott et. al. 2012b). In comparing studies inclusive of this technology with those that are not displays the impact of snowmaking on season length, which “cannot be overstated” (Scott & McBoyle 2007, pp. 1416). As such, the methodology employed in these second-generation studies uses daily historical climate data to model baseline (1961-1990) average season length and snowmaking. Following this, climate change scenarios are downscaled to the site level for the purpose of projecting potential changes to season length and snowmaking (Scott et. al. 2002). This approach has been duplicated in other ski regions, including its use in this current research, with more recent studies corroborating the initial findings of Scott, Jones, Lemiuex, McBoyle, Mills, Svenson and Wall (2002)

Scott et. al. (2003) provide the first peer-reviewed second-generation assessment of future ski operations under climate change that incorporated snowmaking for a southern Ontario ski area. Using a locally calibrated ski operations model (SkiSim 1), the results indicate that under natural conditions (no snowmaking) the number of days where the minimum operational snow depth (30 cm) is met will be reduced by 50 – 96% by the 2050s. With current snowmaking technology, defined as being able to make snow at -5°C at a rate of 10cm/day, the number of days meeting the minimum snow depth will only be reduced by 7%-32% by the 2050s (Scott et. al. 2003). With improved snowmaking technology, defined as being able to make snow at -2°C at a rate of 15cm/day, season length reductions are only projected to range between 1% - 21% (Scott et. al. 2003). These results display the importance of snowmaking, and advanced snowmaking more so, to reduce vulnerability to climate change.

Scott et. al. (2006) expanded on the 2003 study, focusing on ski operations in Ontario, Quebec, Michigan and Vermont, by incorporating additional factors that affect the sustainability of ski operations; season length, probability of being open during the Christmas/New Years and school break period (March), costs of additional snowmaking and water requirements for additional snowmaking. The authors compared their results to prior studies that did not include snowmaking and concluded that adverse consequences from climate change "under the high impact 2050s scenario in this study ('worst case') approximated the low end of the impact range ('best case') from earlier studies" (Scott et. al. 2006, pp. 389).

Scott, McBoyle and Minogue (2007) again applied SkiSim 1 to assess the implications of projected climate change on ski operations, focusing solely on southern Quebec. The results of this work indicate that climate change does not pose a threat to ski operations in southern Quebec by the 2020s, and if snowmaking is employed an adequate snow base can be maintained until the 2050s (Scott et. al. 2007). However, the costs of relying on artificial snow in supplying a consistent ski product, coupled with lost revenues due to contractions in season length or visitation, may exceed the adaptive capacity of two out of the three ski areas examined (Scott et. al. 2007).

Scott et. al. (2008b) adopted a similar approach to Scott et. al. (2003, 2006, 2007), assessing the Northeast USA's ski area. Results indicate that snowmaking will be pivotal in upholding the '100-day' economic guideline (Scott et. al. 2008b). Optimistically, only half of the sub-regions within the Northeast examined can be considered at risk by the 2050s from climate change; identified as season length <100 days and <75% probability of being open during the revenue critical Christmas/New Years segment (Scott et. al. 2008b). These projections exemplify the concept of 'winners and losers' from climate change.

The methodology and ski operations simulation model discussed above were further developed (SkiSim 2.0) and applied to ski resorts in the Tyrol ski region in western Europe (Steiger 2010). The impacts on season length using the updated model are consistent with the trends outlined above; potential adverse impacts from climate change are reduced when snowmaking is incorporated into projections (Steiger 2010). The developments added to SkiSim 1 are discussed in the subsequent Methods chapter since this model is used in the current study.

Steiger (2010) found that when only considering natural snow reliability for a ski area in Tyrol, Austria, operations would be snow reliable until the 2020s under a high-emission (A1B) scenario and until the 2030s under a lower-emission (B1) scenario. When inclusive of snowmaking, the 100-day rule can be fulfilled until the 2050s and 2070s respective of the A1B and B1 GHG emission scenarios (Steiger 2010). A second ski area examined, which is not currently naturally snow reliable, can sustain a 100-day season until the 2040s (A1B) and 2060s (B1) with snowmaking (Steiger 2010). Finally, a third ski area examined was found to be snow reliable until the 2060s under the A1B scenario, continuing until the end of the century under the B1 scenario, with snowmaking (Steiger 2010).

Expanding the geographic region assessed using the SkiSim 2 model, Steiger (2011a) examined the climate change vulnerability of the entire Tyrol (Austria/Italy) ski tourism region. Steiger (2011a) subdivided this region into North Tyrol (NT) and South Tyrol (ST), according to the continental divide, with results indicating that in the B1 emission scenario 100% of ski areas in NT will be able to uphold the 100-day rule until 2050s, while in ST 100% of ski areas will be able to uphold this until the 2060s (Steiger

2011a). Furthermore, the probability of being open during the Christmas/New Years segment is diminished (-15%) in NT by the 2020s while not being affected until the 2040s (-5%) in ST under B1 GHG emission scenario conditions (Steiger 2011a). Under A1B emission scenario conditions, ski areas will not be able to uphold the 100-day rule by the 2040s in NT (-7%) and 2050s in ST (-18%) (Steiger 2011a). Of concern, the Christmas/New Years period is diminished by nearly 50% by the 2050s in both NT and ST (Steiger 2011a). Meanwhile, artificial snowmaking to uphold the 100-day rule will need to be doubled by the 2050s, and tripled by the 2080s, for the entire Tyrol region under the A1B GHG emission scenario conditions (Steiger 2011a).

Clearly, these results from second-generation assessments highlight the importance of future snowmaking technology for sustained ski operations. To date, the methodology and ski operations simulation model (SkiSim) in use throughout northeastern North America and western Europe has greatly improved the outlook of future ski operations, while at the same time increased the interest in assessing the sustainability of critical adaptation strategies such as snowmaking.

Western North America Ski Industry Climate Change Assessments

It is important to set the precedent that none of the subsequent studies examining ski operations in western North America directly model ski operations. They all suffer from some or all of the key methodological limitations outlined above. The impacts of these limitations are more pronounced, as the following constitute the only studies to date. Thus, they could project an overtly negative future for ski tourism in western North America.

For California, Hayhoe et. al. (2004), examined changes to seasonal snow pack through a snow water equivalent (SWE) analysis and predicted that "SWE decreases substantially in all simulations before mid-century" (pp. 14245). They also concluded snowfall would begin later in the winter season, from which they infer that ski area openings will occur later while being forced to close earlier, restricting season length (Hayhoe et. al. 2004). The findings are alarming as they indicate impacts will be worst at elevations under 3000m; the altitude at which the majority of snow pack storage occurs, but also because many of California's ski areas range in elevation from 2000-2500m (Hayhoe et. al. 2004).

Under all scenarios and timeframes assessed ski seasons are predicted to shorten in California (Hayhoe et. al. 2004). Using the National Center for Atmospheric Research/Department of Energy Parallel Climate Model (PCM), the authors predict the season will begin 22 (B1) to 29 (A1Fi) days later, with a total reduction of 49 -103 days, by 2100 (Hayhoe et. al. 2004). When using the Hadley Centre Climate Model 3 (HADCM3) similar delays as those predicted using the PCM model are expected by 2050, though the authors do not outline if this is inclusive of projected season length as well as delayed openings. However, when projected to 2100, season length is expected to be begin 36 days (B1) later while the minimum snow threshold for ski operations is not crossed under the A1Fi scenario, they do not provide finite ski season length reductions using the HADCM3 model (Hayhoe et. al. 2004).

These predictions are inaccurate of the residual impact from climate change because they assess the natural snow reliability of the area instead of ski season length, which they claim. Also, they assess an inappropriate timeframe (2100) that is not considered relevant to business operations by the ski industry (Scott et. al. 2012b). Lastly, Hayhoe et. al. (2004) do not include snowmaking. To date this provides the only known quantified assessment of the vulnerability of California's ski industry, a primary motivation for this current study.

Colorado's ski industry has been the focus of multiple climate change vulnerability assessments. Similar to California, none of these directly model ski season length or operations. Zimmerman, O'Brady and Hurlbutt (2006) apply a similar SWE assessment methodology as Hayhoe et. al. (2004), however, further limiting their work, these authors only consider SWE on April 1, which is an insufficient assessment to realistically project impacts to ski season length. These authors also project impacts to 2085, which is an inappropriate timeframe for current operational decisions. (Scott et. al. 2012b). Their findings indicate that many areas in the Rockies will experience a decrease in snowpack by the year 2085 with resultant impacts on winter alpine tourism; "Most ski counties in Colorado, however, are predicted to lose around 50 percent [of snow pack]…predictions for future mountain climate are warmer winters and shorter snow seasons" (Zimmerman et. al. 2006, pp. 99). The authors state that the implications are that snow dependent mountain activities - such as skiing, tubing and snowshoeing - will continually decrease in popularity as conditions worsen and could become unviable as of 2050 (Zimmerman et. al. 2006).

Woodford, Quartarone, and Berg (1998) depict a similar future for Colorado's ski industry; "snow cover could be diminished in extent, duration and depth…the actual snow season could be shortened by more than 30 days" (pp. 35). Snowfall is expected to occur later in the year with snowmelt occurring earlier, while the snow line is anticipated to rise between 100m and 400m (Woodford et. al. 1998). The implications for the ski industry, as outlined by the authors, are a reduced total number of skiable days jeopardizing the ability to uphold the 100-day rule, inferior conditions, a restriction of activity to higher altitudes and less inter-seasonal reliability (Woodford et. al. 1998, Center for Integrative Environmental Research 2008). Importantly, these authors only consider natural snowfall, increasing the likelihood of potential impacts being exaggerated.

Battaglin, Hay and Markstrom (2011) used a water-shed modeling approach to determine the potential impact of climate change on stream flow, SWE and snow covered areas for two Colorado river basins. From this, they suggest impacts to ski season length. Their results suggest that SWE and snow covered area will be decreased as a result of continued climate change, they identify future reductions to these as likely to contract ski operations in the shoulder seasons (Battaglin et. al. 2011). The authors assert that ski areas' locations are presumably selected in part due to their likelihood to receive and then maintain snow covered area and SWE prior to other nearby locations. This proved true, and vital in future projections at the sub-basin scale as ski area locations were shown to establish and then maintain these indicators better than other regional locations (Battaglin et. al. 2011). Two key limitations to their work are the exclusion of snowmaking and the altitude at which they project changes is analogous with the ski areas' (Steam Boat and Crested Butte) minimum altitude. This altitude is considered most at risk from projected climate change, thus projections are unlikely to represent impacts at higher altitudes (Scott et. al. 2006, 2007, 2008, Steiger 2010, 2011).

A study using a Snowmelt Runoff Model also projected season length reductions for the Colorado ski industry, specifically examining Aspen ski area (Lazar & Williams 2008). The model employed in this study examines whether snow is present at various altitudes and dates, what density the snow has and the likelihood of an avalanche occurring. The authors indicate that until 2100 high altitude operations will retain snow under all future scenarios while the bottom two-thirds will only retain snow under low emission scenarios (Lazar & Williams 2008). The timing of avalanches is likely to occur between two and nineteen days earlier at ski areas' top elevation, occurring between six and twenty-two days earlier at the base elevation by 2030 (Lazar & Williams 2008). By 2100 the timing of avalanches is likely to vary, occurring between sixteen to forty-five days earlier at the top altitude and twenty-two to sixty-five days earlier at the base (Lazar & Williams 2008). The authors state that avalanches will be more likely to occur during the operational season forcing managers to close "portions of the available terrain before snow coverage would otherwise dictate, which could have substantial economic impacts" (Lazar & Williams 2008, pp 226).

Media Coverage of Climate Change and Ski Industry

Media coverage of climate change and tourism has greatly expanded in recent years with ski tourism receiving significant coverage. This is again due to its direct reliance on favourable climate conditions but also because of the obvious impacts during snow deficient seasons (Scott et. al. 2008b). A review of news coverage and headlines for Colorado's and California's ski industry instills imagery of an industry destined to fail; "with all facts pointing to a warming planet, the 2011-12 season should serve as a wake-up call to…any Colorado person who benefits from a thriving ski industry – essentially all of us" (Kuehn 2012). Below, Table 2.4 provides a sample of news headlines for the ski industry in Colorado and California.

Table 2.4: Media Coverage of Climate Change and Ski Industry in Western USA

Headline	Date	Source
Ski Season Seeking Snow	9.1.12	CNN.com
Endless Summer: Ski Resorts Struggle to Keep Terrain Open in New Climate Frontier	3.28.12	The Colorado Independent
Global Warming Impacts Adding Up for Ski Industry	1.30.10	Summit County Citizens Voice (Co.)
Colorado Ski Industry Could 'Melt Away'	11.20.09	Summit Daily News (Co.)
Climate Report Paints Grim Outlook for Ski Areas	2.2.10	Watchnewspapers.com
Climate Change-The End of Sierra Skiing?	3.23.12	Bay City News Service

The media is an important influence on public perceptions of climate change and the impact on ski operations as it is the primary source of information for most participants (Scott & McBoyle 2007, Scott et. al. 2012b). The overtly negative claims must be considered when planning adaptation strategies as they have been shown to impact visitation levels. According to Scott et. al. (2008a) "perceptions of climate conditions or environmental change are just as important to consumer choices as the actual conditions (pp 32). As cited by Scott et. al. (2012b), the media's claims are particularly important to consider during periods or seasons of extreme weather events since tourists have identified reluctance to travel and alternative destination selection in the years following such occurrences. The extremely snow deficient 2011/12 season in North America is an example of this, noting the captions in Table 2.4.

Conclusion

From the preceding discussion it is fair to state that the earth's atmosphere has experienced a considerable level of change in its major constituents since the dawn of the industrial era. These changes have been shown to have impacts on global surface temperatures and the cryosphere, amongst other indicators. Also, the tourism industry has been detailed, including major trends and economic markers. The relationship between climate and tourism has been outlined with particular emphasis given to the ski industry. From this it is clear that the ski industry is one that directly relies on favourable climatic conditions for success. The shortfalls and limitations within the methodological approaches employed in these previous studies for western North America's ski industry, along with the negative portrayal by the media, inspired this assessment. When focusing on the current body of literature in this region no study to date directly attempts to model either ski operations or ski season length. Notably, many studies to date have not adequately incorporated adaptation strategies into their vulnerability assessments, a primary motivation for this assessment.

3. Methods

Introduction

To explore the research questions outlined in chapter 1, quantitative research methods were employed in modeling current and future ski season length and snowmaking requirements. Historical weather data was obtained, and future climate change scenarios applied, to project the potential impacts on the Colorado and California ski industry. The methodology applied in this research builds on that conducted for other leading assessments of climate change and the ski industry in eastern North America and western Europe (Scott et. al. 2003, Scott et. al. 2007, Scott et. al. 2008b, Steiger 2010, Steiger 2011).

Study Areas

The NSAA segregates the American ski industry into either five or six regions, depending on their analysis of the industry (NSAA 2010, NSAA 2011a). For the purposes of this research, two ski areas were selected from the Rocky Mountain as well as one from the Pacific West (Pacific Southwest) region (NSAA 2010, NSAA 2011b). Figure 2.2 displays where the ski areas examined in this study are located within the western United States, while Figure 2.3 and Figure 2.4 display their locations within Colorado and California respectively.

Colorado

Colorado is home to 26 ski resorts with some of the highest elevation skiing in the lower 48 states (Colorado Tourism Office 2012). Of these 26 resorts, 22 are members of the Colorado Ski Country USA initiative (CSCUSA), a statewide non-profit organization dedicated to measuring and improving the Colorado ski industry (Colorado Ski Country USA 2012). When only considering these 22 resorts the average base elevation for a ski area in Colorado is 2747 masl, the average peak elevation is 3452 masl, resulting in a average vertical rise of 710 masl for these ski areas (CSCUSA 2012a). The highest peak elevation for any resort in Colorado, regardless of its membership in the CSCUSA, is 4111masl. The absolute lowest base elevation is 2041 masl, displaying the range in elevation for this industry in Colorado (CSCUSA 2012a). In Colorado, the 10-year average for snowfall amongst CSCUSA resorts is 795 cm, and those 22 resorts encompass a total of 28,971 acres of skiable area (CSCUSA 2012a). The 4 ski areas not a part of the CSCUSA account for 12,360 additional skiable acres, in total there are 41,601 skiable acres in Colorado, a figure that translates to 168 square kilometers (onthesnow.com 2011). Amongst the 22 CSCUSA member resorts, 3623 acres are currently equipped for snowmaking, a figure that increases to 5853 acres when including the 4 additional resorts, roughly 14% of all skiable terrain in the state (CSCUSA 2012a; onthesnow.com 2011).

Visitation among the CSCUSA member resorts has increased 9% over the 10-season period ranging 2001/02 to 2010/11 (CSCUSA 2012a). Considering that the CSCUSA does not include the Vail, Breckenridge, Beaver Creek or Keystone ski areas these figures do not fully represent changes in visitation levels. According to independent reviews of the Colorado industry these 4 non-member resorts, specifically Vail, Breckenridge and Keystone, are amongst the most popular and are more likely to attract international participants (onthesnow.com 2011). Thus, considering the steep increase in international visitation stated in the Kottke the more recent visitation numbers from CSCUSA are likely an under estimate of the true growth of the state's ski industry over the last ten years (NSAA 2011a).

Colorado ski areas were selected from within the Rocky Mountain region because this state, in the 2010/11 season, recorded the single largest number of skier visits (12.3 million) (NSAA 2011a). Table 3.1 presents a statistical breakdown of Colorado ski resorts considered for this study. Those not included did not meet the requirements for proximity to a climate station with sufficient historical daily climate records.

The two Colorado case studies selected in this study were primarily chosen due to their proximity to climate stations with suitable data. Multiple ski areas fulfilled this requirement for the Vail climate station, as such, the Vail and Copper Mountain ski areas were chosen due to their outstanding characteristics. Between them nearly the full altitudinal distribution of ski areas within Colorado is covered; Vail's operations are in the lower 25% and Copper Mountain's in the upper 25% of the altitudinal range in Colorado. Furthermore, Vail was selected due to its international prominence as a ski destination. Copper Mountain was subsequently selected to provide a comparison to

Vail's relatively low altitude operations in an attempt to highlight the importance of elevation on ski operations.

Table 3.1: Colorado Ski Areas Considered in This Study

Ski Area	Summit (masl)	Base (masl)	Rise (m)	Terrain (acres)	Snowmaking (%)
Arapahoe Basin	3978	3286	692	900	14
Aspen Highland	3559	2451	1108	1028	N/A
Aspen	3417	2422	673	1028	N/A
Buttermilk	3018	2399	619	470	N/A
Breckenridge	3962	2962	1036	2378	24
Beaver Creek	3487	2469	1018	1815	13
Crested Butte	3707	2858	849	1250	23
Durango Purgatory	3299	2680	619	1200	21
Echo Mountain	3246	3063	183	85	71
Eldora	3292	2804	488	680	74
Howelson	2175	2041	134	25	N/A
Keystone	3719	2835	884	3148	21
Loveland	3965	3231	735	1600	10
Snowmass	3813	2470	1343	3132	N/A
Copper Mountain	**3753**	**2960**	**793**	**2465**	**15**
Vail	**3527**	**2475**	**1052**	**5289**	**9**

Data source: onthesnow.com (2011), Colorado Ski Country USA (2012a)

Vail

Vail ski resort is located in the town of Vail, Colorado, approximately 160 km west of Denver, Colorado. Vail is one of the most widely known ski areas in the world, and certainly one of the most popular in the American ski industry (onthesnow.com 2011). The resort website claims that it is the largest ski resort in America, encompassing "5,289 acres of the most diverse and expansive skiing in the world" (Vail Resorts Management Company 2011). Of this acreage, only 461 acres are currently equipped with snowmaking technology, approximately 8.7% of all skiable acreage (Vail Resorts Management Company 2011). Vail is home to 193 conventional trails, with additional backcountry skiing possible [53% of the ski area is considered expert while 29% and 18% are considered intermediate and beginner, respectively] (Vail Resorts Management Company 2011). Vail's vertical transfer rate, which estimates the total number of skiers that could be transported from the base elevation to the summit elevation in one hour, is 59,092 people (Vail Resorts Management Company 2011).

Typical ski seasons last from mid-November to mid-April, however, there is some annual variation dependent upon weather conditions and operational decisions (Vail Resorts Management Company 2011). Average visitation over the ten-year period spanning the 2001/02 to 2010/11 seasons was 1,609,580 visits; the 2010/11 season saw the largest total number of visits reaching 1,750,000 (Vail Resorts Management Company 2011). Despite Vail's prominence and large area of terrain it is not an exceptionally high elevation ski area relative to other Colorado ski areas. Its base elevation is 2467m while its peak is 3,125m, resulting in a vertical rise of 1,052m (Vail Resorts Management Company 2011).

According to the resort website, Vail receives 929 cm of snowfall each year, which is a questionable statistic given the more reliable figures provided through state and federal weather agencies; the Vail climate station, for the baseline climate period, received average annual snowfall of 490 cm (Vail Resorts Management Company 2011, Western Regional Climate Center 2012). The questionable nature of self-reporting of snowfall by ski areas is common in the industry.

Copper Mountain

Meeting the same criteria as Vail, this site was selected primarily due to its proximity to a climate station with reliable historic climate records. Beyond this, Copper Mountain was chosen to provide a comparison to Vail of the potential impacts to ski operations from projected climate change. Since Copper has a higher average elevation than Vail it will provide a means to evaluate the influence of elevation on ski operations under climatically warmer futures.

Copper Mountain ski area is located approximately 130km west of Denver (Copper Mountain 2011). It is located at a higher elevation than Vail, however, its vertical rise is slightly less; Copper's base elevation is 2926m while its summit elevation is 3767, resulting in a vertical rise of 793m (Copper Mountain 2011). The resort website boasts about Copper's family-friendly atmosphere and varied terrain, making it suitable for participants of all ages and abilities (Copper Mountain 2011). In total, it covers an area of 2465 acres, of which 380 acres (15%) are equipped for snowmaking (Copper Mountain 2011; onthesnow.com 2011). Copper has a vertical transfer rate of 32,324 visitors per hour with 126 marked trails; 26% beginner, 25% intermediate, 36% advanced and 18% expert (Copper Mountain 2011).

California

California is home to 27 ski resorts, providing over 32,000 acres of skiable terrain, the equivalent of 130 square kilometers (onthesnow.com 2011a). However, terrain information for three smaller state-run resorts was unavailable at the time of writing, reducing the total skiable terrain reported (onthesnow.com 2011a). Of the 24 resorts whose information was available, the highest peak elevation among Californian ski areas is 3369 masl while the lowest base elevation is recorded at 1676 masl (onthesnow.com 2011a). The California Ski Area Association, commonly referred to as California Snow, is a non-profit organization whose mandate is to support resorts by coordinating legislatives, risk management and technical training for the industry (California Snow 2011). Comprehensive ski industry data relating to visitation and growth, such as that presented for Colorado, is unavailable for California.

The ski industry in California was chosen for analysis in this study to provide a comparison to the Colorado ski areas. This comparison has the potential to provide valuable insight into the projected impacts of elevation on ski season length and snowmaking since California's ski areas are on average less high. Supporting this selection, in the 2010/11 season California recorded the second largest number of skier visits at 7.4 million, second only to Colorado (NSAA 2011a). Additionally, California is home to a large number of ski areas of international notoriety. Specifically, the Lake Tahoe ski region within California was selected because it boasts a high density of ski areas in a relatively confined geographic area. Table 3.2 outlines ski areas in California considered for this study, only those that met the proximity to a climate station requirement are presented.

Table 3.2: California Ski Areas Considered in This Study

Ski Area	Summit (masl)	Base (masl)	Rise (m)	Terrain (acres)	Snowmaking (%)
Alpine Meadows	2633	2083	549	2400	20
Boreal	2347	2195	152	380	75
Donner Ski Ranch	2363	2057	305	505	N/A
Heavenly Ski Resort	3068	2001	1067	4800	73
Homewood Mountain	2402	1899	503	1260	10
Kirkwood	2987	2377	610	2300	2
North-Star-At-Tahoe	2624	1929	695	3000	50
Royal Gorge (X-country)	2256	2079	177	9000	N/A
Sierra-at-Tahoe	2698	1920	674	2000	4
Soda Springs	2240	2042	198	n/a	N/A
Sugar Bowl	2555	2098	457	1500	25
Squaw Valley	**2758**	**1890**	**868**	**3600**	**10**

Data source: Skitown.com (2011a), onthesnow.com (2011a)

Squaw Valley

Squaw Valley ski resort is located in the Sierra Nevada Mountains in northern California, it is in the Lake Tahoe ski region approximately 10 km northwest of Tahoe City (Squaw Valley 2011). The resort website highlights the area's pristine natural environment and excellent weather conditions; claiming to receive 11.15m of snowfall each year (Squaw Valley 2011). Similar to Vail and Copper Mountain, this amount of snowfall is unlikely as it contradicts more reliable sources of snowfall data such as state and federal sources, which indicate that average annual snowfall between 1961-1990 was 457 cm (Western Regional Climate Center 2012a). Regardless, Squaw is home to 3600 acres of skiable terrain, 600 acres (16.6%) of which are currently equipped with snowmaking technology (Squaw Valley 2011). At its base, its elevation is 1890m while its peak elevation is 2758m, providing a vertical rise of 869m (Squaw Valley 2011). Uniquely, Squaw Valley has six peaks within its skiable area allowing for participants of all abilities to find appropriate runs to enjoy the sport (Squaw Valley 2011). Squaw Valley has over 170 different ski runs, a figure that varies depending on weather conditions, 25% are classified as beginner while 45% are intermediate and 30% advanced (Squaw Valley 2011). It has a vertical transfer rate of approximately 49,000 people per hour (Squaw Valley 2011).

The Squaw Valley ski area fulfills the main methodological requirement of ski areas in this study as it is located within 50 km of a climate station with reliable baseline period records, including daily precipitation, maximum and minimum temperature, snowfall and snow depth information. This was the primary consideration in its selection. Beyond this, it is similar in size to Vail but at a lower average elevation, allowing for a better comparison of projected impacts. Lastly, Squaw Valley represents a significant portion of ski areas in California as its elevation range encompasses nearly the full spectrum of skiing in the state, displayed in Table 3.2.

Data Sources & Long Ashton Research Station-Weather Generator

Climate Station Selection

Weather data for this research was obtained through the National Climatic Data Center (NCDC), a subsidiary of the National Oceanic Atmospheric Administration (NOAA). The methodology applied in selecting stations to represent the selected ski hills follows the methodologies from other second-generation assessments of climate change and the ski industry (Scott et. al. 2003, Scott et. al. 2007, Scott et. al. 2008b, Steiger 2010, Steiger 2011). As stated, the distance between ski areas and climate stations was a primary consideration for the selection of each. In addition to distance, elevation was an important consideration during the ski area and climate station selection process. Ski areas and climate stations must also have been at a relatively analogous altitude; having approximately 500 m or less difference between the climate station and some point of the ski area, preferably its base. Beyond these considerations, the final selection of climate stations was dependent upon the length and quality of historical climate records. If a station did not have sufficient, daily weather records for precipitation, maximum and minimum temperature, snowfall and snow depth, regardless of its proximity to ski areas, it was eliminated as a consideration.

Through this process the NCDC climate station Vail (Station ID: GHCND:USC00058575, 39.64°, -106.35°) was selected to represent the Colorado case studies. Its elevation is 2531masl, located 64 m above Vail ski area's base operations and 395 m below Copper Mountain's base operations. Vail climate station is located approximately 3 km from the Vail ski resort and 24 km from the Copper Mountain ski resort. The NCDC climate station Tahoe City (Station ID: GHCND:USC00048758, 39.18°, -120.14°) was chosen to represent the Californian case study. This station's elevation is 1898.9 masl, 10 m difference from Squaw Valley's base elevation, and located approximately 9 km from the ski area. Thus, these climate stations were determined to be most suitable for representing daily weather conditions at each ski area.

Daily weather data was obtained for each site in question. This data was used in establishing the baseline climate, which served two central purposes: calibrating SkiSim 2 for the respective ski areas, and downscaling future climate change scenarios to the site level. The data for these stations were formatted for input into the Long Ashton Research Station-Weather Generator (LARS-WG), which analyzed daily precipitation as well as daily maximum and minimum temperature. It was also formatted for input into SkiSim 2, which required daily snowfall and snow depth information in addition to precipitation and temperature.

Table 3.3 outlines the observed 1961-1990 climatology data for the Tahoe City climate station. This data was used as input into both LARS-WG and SkiSim 2, as described below, for generating the baseline climate file as well as calibrating the SkiSim 2 model to local conditions.

This station had data for all variables outlined spanning the 1961-1990 period with minor gaps in daily values requiring minimal data infilling. For this station, data infilling requirements centered on particular months with missing climate station data. In these instances entire months of climate data were unavailable due to station maintenance work or disruptions in data collection. These missing months were excluded from averages and modeling through adjustments in LARS-WG and SkiSim 2 formatting that circumvented this missing information. Beyond this, occasional snow depth values were required to be supplemented. In these instances, snow depth was typically unavailable for a particular day, to overcome this, snow depth from the previous day was assumed to remain constant if temperatures were below zero and precipitation recorded at zero. If snow depth data was unavailable on days with temperature above zero, an average snowmelt rate was applied to the next subsequent day with snow depth data. This average was calculated based on the rate of snowmelt over a time period relevant to the missing day, typically a few weeks to a month.

Table 3.3: Observed Tahoe City Baseline Climatology 1961-1990

Month	Maximum T (°C)	Minimum T (°C)	Precipitation (mm)	Snowfall (cm)	Snow Depth (cm)
January	4	-7	142	96	53
February	5	-6	123	82	69
March	7	-5	103	92	60
April	10	-3	51	43	28
May	15	0	25	10	5
June	20	4	22	1	0
July	25	7	8	0	0
August	25	7	13	0	0
September	21	4	23	1	0
October	15	0	52	6	0
November	8	-3	119	49	9
December	5	-6	137	80	28

Data source: Western Regional Climate Center (2012a)

Records for Vail climate station began in 1985 continuing to present day, requiring these records to be supplemented for use in this study. Vail's observed climatology data for the 1985-2010 period is outlined in Table 3.4. In the same fashion as for the Tahoe City climate station, this data was used as input into both LARS-WG and SkiSim 2, as described below, for generating the baseline climate file as well as calibrating the SkiSim 2 model to local conditions.

To create a 1961-1990 baseline period, Vail's 1985-2010 data was supplemented through a comparative analysis with the nearby NCDC climate station Dillon 1E (GHC ND: USC00052281, 39.63° -106.04°, 2763m), located 27 km away. The two data sets were merged according to techniques set out in Steiger (2010, 2011a). This approach was chosen since within LARS-WG larger quantities of historic data allows for a more accurate representation of statistical distributions (Semenov et. al., 1998). The revised approach also allowed for a direct comparison to the Lake Tahoe region and other studies of the same nature as it provided the same baseline climate period.

Table 3.4: Observed Vail Climatology 1985-2010

Month	Maximum T (°C)	Minimum T (°C)	Precipitation (mm)	Snowfall (cm)	Snow Depth (cm)
January	-2	-14	48	86	64
February	1	-13	53	84	79
March	6	-8	46	61	66
April	10	-4	56	56	28
May	16	-1	46	13	3
June	22	2	38	0	0
July	26	5	51	0	0
August	24	4	48	0	0
September	19	1	53	3	0
October	12	-4	43	20	0
November	3	-9	48	71	15
December	-2	-14	41	71	38

Data source: Western Regional Climate Center (2012)

Long Ashton Research Station – Weather Generator

This study employed the LARS-WG, a stochastic weather generator, to create the baseline and future climate change scenarios. A stochastic weather generator is a tool that can create synthetic, site-specific, weather data from observed weather patterns (Semenov, Brooks, Barrow & Richardson, 1998). Weather generators are not meteorological models and do not attempt to replicate observed weather, rather they calculate the distribution of dry and wet days as well as temperature and solar radiation flux through statistical modeling (Semenov et. al., 1998). These calculations are then used to create statistically analogous synthetic weather (Semenov et. al. 1998). While weather values for any given day produced by LARS-WG are not likely to match that of the observed patterns, the synthetic year is statistically identical for the occurrence of various weather events (Semenov et. al., 1998).

LARS-WG was selected for use in this study as it can produce site-specific daily weather data for multiple years with the ability to account for climate change as well as inter-season variability (Scott et. al. 2003). It has been shown to have superior performance above other weather generators with respect to precipitation patterns (Scott et. al. 2003).

Climate Change Scenarios

To examine the impact of potential future climate change on ski season length, monthly climate change scenarios from GCMs were obtained at the state level for each case study. All GCMs used were constructed in accordance to the IPCC's climate modeling inter-comparison project (Pacific Climate Impacts Consortium 2011). The SRES emissions scenarios were employed in this study as they provide reliable projections of potential future climate change, also the precedent for their use was established in previous ski area climate change vulnerability assessments (Scott et. al. 2003, Scott. et. al. 2006, Scott et. al. 2007, Scott et. al. 2008b, Steiger 2010 & Steiger 2011). Their use allows for a direct comparison between the results of this work with previous research.

The climate change scenarios were selected using the Pacific Climate Impacts Consortium (PCIC) Regional Analysis Tool. The selection of climate change scenarios for this project was based on the distribution of uncertainty in the level of change expected for both temperature and precipitation. The selection criterion applied follows that of Scott et. al. (2006);

> "In order to limit the number of scenarios to a manageable number, while still considering the full range of potential climate futures, scenarios representing the upper and lower bounds of change in December-January-February (DJF) mean temperature and precipitation were selected for this analysis" (pp. 382).

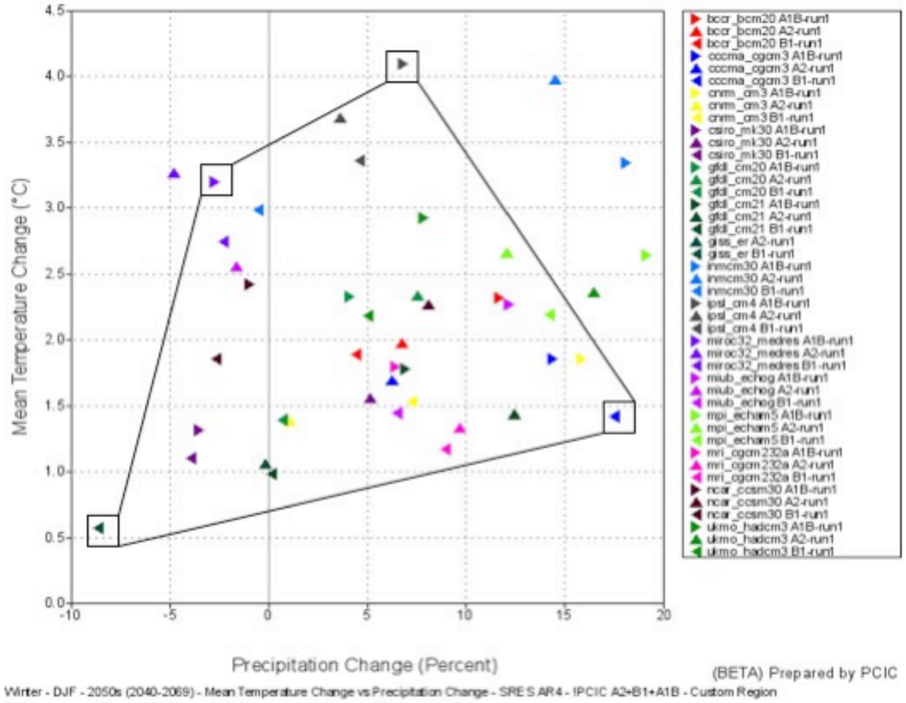
The four scenarios selected for both Colorado and California are; the Goddard Institute for Space Studies B1 (GISS B1) scenario, the Canadian Centre for Climate Modeling and Analysis B1 (CCCMA B1) scenario, the Model for Interdisciplinary Research on Climate A1B (MIROC A1B) scenario, and the Institut Pierre Simon Laplace A1B (IPSL A1B) scenario. Figure 3.1 and Figure 3.2 display the range of future climate change projections for the 2050s (2040-2069) for Colorado and California, respectively (the four scenarios used in this study are circled).

The two former scenarios (GISS B1, CCCMA B1) are herein referred to as the ‘least change’ scenarios, while the latter two scenarios (IPSL A1B, MIROC A1B) are herein referred to as the ‘most change’ scenarios, relative to the 1961-1990 baseline period. While the 2020s (2011-2039) climate change scenarios are most relevant to ski area managers, projected climate change in this period does not substantially differ from current climate variability. The real value of the SkiSim 2 modeling approach is that it allows ski industry (and other tourism) stakeholders to explore the potential impacts of conditions they have not experienced (e.g. beyond the climate change analogues of recent record warm winters). The 2050s timeframe was selected as it allows enough time to elapse for significant changes to average climate to occur while not exceeding the decision-making timescale of operational managers (Scott. et. al. 2003).

For Colorado, these four scenarios encompass almost the full distribution of uncertainty in future change. Of the two ‘most change’ A1B scenarios, one accounts for relative increases in precipitation while the other accounts for relative decreases, the same is true of the ‘least change’ B1 scenarios.

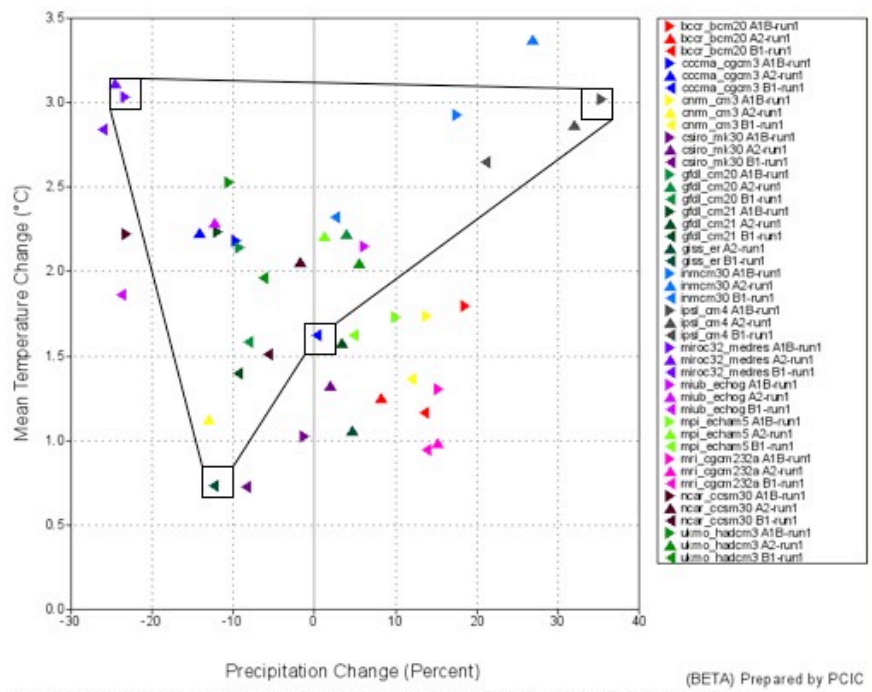
For California, the full distribution of uncertainty in future change is not covered since a scenario representing minimal temperature increase with relative precipitation increases is not examined. The California climate change scenarios were selected following Colorado, thus the same four change scenarios were chosen to facilitate fuller comparisons between these sites. For California, the CCCMA B1 scenario is deemed a ‘middle of the road’ scenario for future change. Lastly, of the four future change scenarios the two ‘most change’ predictions accurately represent the upper limits of temperature increase for the 2050s timeframe while the GISS B1 scenario accounts for the least temperature change of all future scenarios at both locations.

Figure 3.1: Colorado 2050s Climate Change Projections*



Source: Pacific Climate Impacts Consortium 2011
*Boxed scenarios utilized in this study

Figure 3.2: California 2050s Climate Change Projections*



Source: Pacific Climate Impacts Consortium 2011
*Boxed Scenarios utilized in this study

In comparing California's projections of climate change with those for Colorado a clear trend is Colorado's higher expected warming. On average, when assessing annual projections, California is anticipated to experience less temperature increase than its Rocky Mountain counterpart. When assessing winter projections of climate change there is a greater degree of warming anticipated for California in the B1 scenarios and a greater degree of warming anticipated for Colorado under the A1B scenarios during the 2050s.

Regardless of the differences in severity of projected warming, California is expected to experience more substantial impacts to ski operations from climate change due to the selected climate station's baseline climatology. Tahoe City climate station's baseline average winter (December, January, February) temperature is -1°C, whereas Vail climate station's average winter temperature is -7°C (Table 3.3 and Table 3.4). While the warmest of all winter temperature projections are expected for Colorado (A1B scenarios) these are less of a concern than projections for California, as even under this level of warming average Colorado winter temperatures will still be 3-4 degrees Celsius below zero (Table 3.5). Meanwhile, the less severe winter warming for California will result in average winter temperatures between 0-3°C.

Projected changes to precipitation do not follow a distinct pattern as outlined above (Table 3.6). The average change in precipitation varies according to the individual GCMs, as well as annual and winter projections, more than it does between regions. The GISS B1 and MIROC A1B scenarios anticipate reductions in precipitation for the 2050s annually and during the winter for both states. The CCCMA B1 and IPSL A1B scenarios largely anticipate increases in precipitation. The only exceptions are slight annual decreases of 0.5% (California CCCMA B1) and 5.6% (Colorado IPSL A1B). All other CCCMA B1 and IPSL A1B precipitation projections, for both Colorado and California, annual and winter, indicate expected increases.

Table 3.5: Projected Temperature Change 2050s

Average Temperature Increase (°C)								
	GISS B1		CCCMA B1		ISPL A1B		MIROC A1B	
	Annual	Winter	Annual	Winter	Annual	Winter	Annual	Winter
Colorado	1.46	0.58	2.07	1.7	3.82	4.14	3.85	3.14
California	1.15	0.74	1.94	1.83	2.99	2.99	3.22	2.78

Source: PCIC 2011

Table 3.6: Projected Precipitation Change 2050s

Average Precipitation Change (%)								
	GISS B1		CCCMA B1		ISPL A1B		MIROC A1B	
	Annual	Winter	Annual	Winter	Annual	Winter	Annual	Winter
Colorado	-6.7	-8.7	1.8	12.8	-5.6	12.2	-11.9	-3.1
California	-9.4	-12.5	-0.5	5.8	12.4	35.7	-16.2	-19.2

Source: PCIC 2011

Downscaling Climate Change Scenarios

To project changes to ski season length and snowmaking requirements resulting from climate change, monthly temperature and precipitation change signals were taken from the four GCMs outlined above for each state. The state level scenarios were then downscaled to the site level using LARS-WG to generate daily weather for the 1970s (1961-1990) and 2050s (2040-2069) time periods. The result is daily weather values for temperature (maximum and minimum) and precipitation for the baseline period as well as the four climate change scenarios for the 2050s for each study area. These scenarios are used as input into SkiSim 2 in modeling baseline and potential future ski season length and snowmaking requirements (Steiger 2009).

California

For the purposes of this research, monthly climate change projections were used in creating the four future climate scenarios. LARS-WG was used to create scenarios projected to the 2050s using temperature and precipitation change values relative to the 1970s baseline period. California's monthly climate change values, applied to the baseline scenario, are presented in Table 3.7.

Table 3.7: California Monthly Climate Change Projections 2050s

Month	GISS B1		CCCMA B1		IPSL A1B		MIROC A1B	
	T (°C)	P (%)	T (°C)	P (%)	T (°C)	P (%)	T (°C)	P (%)
January	0.7	-10.6	1.9	9.2	3	39.4	3	-23.6
February	0.9	-12.4	2	11.8	3	24.6	2.7	-17.1
March	0.9	6.3	1.8	-1.1	2.7	-0.8	2.8	-14.8
April	-0.1	-4.9	1.5	-13.6	3.1	-11.7	3.4	-29
May	1.1	-29.6	1.7	-1.4	2.4	4.1	3.3	-24.8
June	1.7	-22.2	2	6.4	3.3	-41.2	3.3	-6.2
July	2.1	139.6	2.5	3.1	2.7	-20.9	3.8	-15.6
August	2.3	-16.2	2.4	2.9	3.4	-29.6	3.8	3.6
September	1.9	-3.1	2.4	12	3.8	11.4	3.6	-9.7
October	1	11.9	2	11.9	2.7	7.7	3.3	-13.6
November	0.6	-11	1.7	8	2.9	-11.7	3	-4.6
December	0.6	-13.6	1.6	2.2	2.9	48.7	2.6	-15.7

Source: PCIC 2011

Colorado

The same approach was used for Colorado. As noted above, the average annual change in temperature is higher for Colorado than California, while precipitation change varies according to the GCM selected. The monthly change values applied to Colorado's baseline scenario are presented in Table 4.4.

Table 3.8: Colorado Monthly Climate Change Projections 2050s

Month	GISS B1		CCCMA B1		IPSL A1B		MIROC A1B	
	T (°C)	P (%)	T (°C)	P (%)	T (°C)	P (%)	T (°C)	P (%)
January	0.5	-13.4	1.7	14.8	4.2	11.6	3.5	-7.6
February	0.7	-9.7	2	13	4.4	11.4	3.1	-1.8
March	1.4	-5	1.7	6.5	4.2	-1	3.9	-3
April	0.9	-11.4	1.7	-4.9	4.4	-18.5	4.3	-15.3
May	1.9	-10	2.4	-4.6	3.1	-13.4	3.8	-16.3
June	2.2	-15.2	2.3	-1.1	4	-33.3	4.3	-19.2
July	2.4	-12.9	2.4	3	3.1	-6.6	4.6	-13.1
August	2.6	-2.6	2.4	-3.7	4.1	-11.1	5	-23.7
September	2.5	-4.9	2.7	-4.4	4.3	-16.8	4.6	-6.6
October	1.8	-1.9	2.6	16.2	3.2	-1.6	3.6	-0.8
November	0.5	7.3	1.5	7.6	3.1	-9.6	3.3	-9.4
December	0.5	-2.4	1.4	13.9	3.8	14	2.9	0.8

Source: PCIC 2011

SkiSim 2

SkiSim 2 Overview and Improvements

SkiSim 2 is the second edition of a ski operations simulation model initially developed and used in an analysis of skiing and climate change in southern Ontario (Scott et. al. 2003). Following this analysis SkiSim (1 and 2) has been used to examine climate change and the ski industry in numerous locations throughout Canada (southern Ontario, Quebec, Alberta), the United States (all New England states), western Europe (Austria, Italy) and Australia (Scott et. al. 2003, Scott et. al. 2006, Scott et. al. 2007, Scott et. al. 2008b, Steiger 2010, Steiger 2011a, Scott & Steiger 2012).

SkiSim 2 is a semi-distributed model capable of examining the adverse impacts associated with climate change at multiple elevations of a ski area (Steiger 2009). This is a pivotal improvement to the former SkiSim 1, which was designed to model projections at only one elevation, typically the base (the most vulnerable elevation) or mid elevation of a ski area (Steiger 2009). The significance of this is that the overall vulnerability of a ski are can be assessed, something that was not possible with SkiSim 1 (Steiger 2009). SkiSim 2 produces outputs in 100 m elevation bands for the ski area, allowing the researcher to determine how much more or less an area's base elevation will be impacted compared to its summit elevation.

In addition to the semi-distributed nature of the model, SkiSim 2 uses site-specific, data derived temperature lapse rates whereas SkiSim 1 used a standard elevation lapse rate (Steiger 2009). Temperature lapse rate denotes the relative change in temperature expected with increasing or decreasing elevation (Rolland 2003). Externally derived lapse rates provide more accurate, site-specific projections. They require fewer simplifications in the modeling process providing more accurate results. Lastly, SkiSim 2 has an updated, more sophisticated, snowmaking module due to the incorporation of its semi-distributed projections (Steiger 2009). Again, this allows for enhanced site-specific projections.

Lapse Rate Calculation

As stated above, one of the critical improvements to SkiSim 2 was the inclusion of derived, site-specific, lapse rates for temperature instead of standard lapse rates. These lapse rates are calculated by assessing the change in temperature between two climate stations at different elevations (Steiger 2010). A qualification process was used in selecting these stations similar to the process applied in selecting stations to represent ski areas. Stations had to be within a reasonable distance (50 km) to the station representing the ski area(s), it was required to have at least five years with overlapping data and a reasonable difference in elevation (>300 m). However, assuming the first two criteria were met, stations with the largest difference in elevation were selected.

In Colorado, the NCDC climate station Climax (GHC ND: USC 00051660, 39.37° -106.19°, 3442m) was used in relation to the Vail climate station. Climax is located approximately 33km from Vail, and has a difference in elevation of 911m, with data overlapping 1985-2010 (NCDC). In California, the NCDC climate station Echo Summit Sierra Tahoe (GHC ND: USC 00042671, 38.78° -120.03°, 2240m) was used in comparison to the Tahoe City climate station. This station is 350m higher than Tahoe City and located approximately 45km away with the entire baseline period having overlapping data.

SkiSim 2 Modeling Process

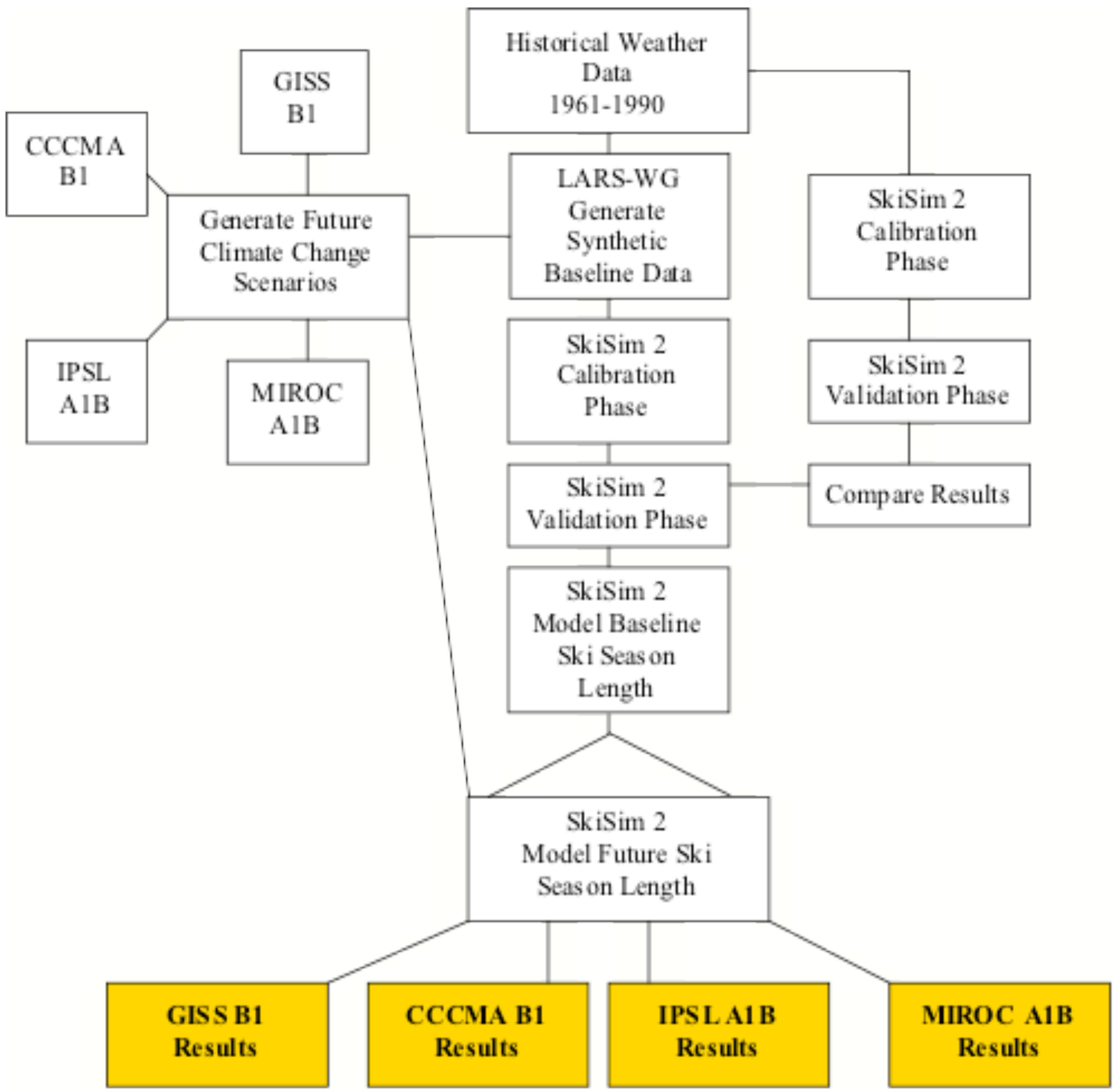
Following earlier assessments that used the SkiSim model (Scott et. al. 2006), this study models the "impact of climate change on a standardized hypothetical ski area" for each case study. The size, snowmaking capacity and location of snowmaking equipment, are assumed to be constant amongst each ski area throughout the SkiSim 2 modeling process. "This effectively isolates the importance of climate and projected climate change at each location" (Scott et. al. 2006, pp. 385). However, each ski area's actual elevation range is utilized to examine the importance of elevation with regards to climate change impacts.

A description of the SkiSim 2 modeling process for this study follows (Figure 3.3). The purpose of SkiSim 2 is to model current ski operations as well as future ski operations under climate change scenarios. In SkiSim 2, ski season length is based on predetermined parameters for defining a 'skiable day'; the primary criterion in defining a 'skiable day' is having 30 cm (or greater) minimum snow depth. Beyond this, ski operations were assumed to end if maximum temperature is greater than 10°C for two consecutive days accompanied with liquid precipitation, or if there were two days of liquid precipitation totaling 20 mm or greater (Scott et. al. 2003). These parameters, established in Scott et. al. (2003), were concluded upon through an examination of observed ski operations as well as communications with ski area managers.

Historic daily weather data for precipitation, maximum and minimum temperature, snowfall and snow depth are used as the input variables to calibrate the physical snow model within SkiSim 2 to local climatology (Steiger 2009). This is herein referred to as the Calibration Phase and can be further broken down into two key processes; 1) calibration of snowfall temperature and 2) calibration of the degree-day factor (snowmelt) (Steiger 2009). To calibrate SkiSim 2 for snowfall both daily maximum and minimum temperatures as well as precipitation are used (Steiger 2009). SkiSim 2 samples a sequence of different temperature thresholds to determine when precipitation falls as either rain, snow or a rain/snow mixture (Scott et. al. 2003, Steiger

2009). The purpose of this is to determine the temperature at which precipitation falls as snow, and the potential for a skiable day (Steiger 2009).

Figure 3.3: SkiSim 2 Modeling Process



Within SkiSim 2, the "critical temperature thresholds (T_{cmin} and T_{cmax}) were calibrated with snowfall data for each climate station…if the mean temperature (T_{mean}) is below T_{cmin} 100% of precipitation occurs as snow; if it is above T_{cmax} 100% of precipitation occurs as rain" (Steiger 2010, pp. 254). If temperature is in between, "the snow/rain ratio is interpolated linearly as: (Steiger 2010)

$$\mathrm{SWE_S} = p\frac{T_{c,\max} - T_{\mathrm{mean}}}{T_{c,\max} - T_{c,\min}}$$

Where SWE_s is the SWE of fresh snow, p is precipitation, T_{cmin} is the minimum critical temperature threshold where snow occurs, T_{cmax} is the maximum critical temperature where rain occurs.

Following this SkiSim 2 calibrates for the degree-day factor, otherwise referred to as the snowmelt factor. However, it is important to note that snowfall must be calibrated first as it is required in modeling the rate of snowmelt (Steiger 2009). In SkiSim 2 a variable degree-day factor, which for this study is 1-5, mm/°C/day, is used to determine snowmelt (R. Steiger, pers. comm..; Steiger 2009). Melt is calculated based on the following equation: (Stegier 2010)

$$M_{\mathrm{pot}} = \mathrm{ddf} \times T_{\mathrm{mean}}$$

Where M_{pot} is the melt potential and ddf is the degree-day factor. The snowmelt factor follows a sinusoidal pattern throughout the year "which is increasing during the snow season (due to snow metamorphosis and higher radiation in the proceeding snow season) and decreasing after snowfall events due to the higher albedo of fresh snow" (Steiger 2009, pp. 2). A range of years within the baseline period are selected for testing these factors, known as the calibration period, the success is judged by comparing modeled accumulated snowfall and snow depth with measured accumulated snowfall and snow depth (R. Steiger, pers. comm..; Steiger 2009).

Once the parameters under which snowfall and snowmelt occur are determined the model then proceeds to validate these, herein referred to as the Validation Phase. During this phase, SkiSim 2 tests the snowfall and snowmelt parameters determined in the calibration phase during a different time period within the baseline years, these years are referred to as the validation period. If, in the validation period, modeled snowfall and snow depth accurately reflect measured conditions, SkiSim 2 is considered to be successfully calibrated and able to model local climatology.

In addition to the physical snow module, SkiSim 2 incorporates a snowmaking module (Scott et. al. 2003, Steiger 2009). This module is used to determine the conditions under which artificial snow can be produced and the extent to which it can be produced. The snowmaking module is based on current technological snowmaking capacities as well as operational decision rules (Scott et. al. 2003). For this study, the technological capacities assumed for snowmaking are that temperatures must be -5°C, or less, in order to produce artificial snow. The decision rules applied for snowmaking are that snowmaking operations may begin November 1, or on the first subsequent day where the technological requirements are met, and conclude April 15 (Scott et. al. 2003). Beyond this, snowmaking is employed in an attempt to establish and then maintain a 30 cm snow pack for ski operations.

The snowmaking module in SkiSim 2 assumes that snowmaking has the ability to cover all (100%) skiable terrain, which is not currently the case for the ski areas analyzed in this study (see Table 3.1 & Table 3.2). This is an important distinction since the projections that follow would have increased adverse impacts if modeling accounted for actual snowmaking coverage. This was not possible at the time of modeling as the location of snowmaking equipment is proprietary information and unavailable. This study assumes that under future climate change, a greater investment in snowmaking will occur, which is in line with ski area managers' intentions (Wolfsegger et. al. 2008).

The final step in assessing the calibration of SkiSim 2 is to model baseline ski seasons. The output is a sample baseline season, measured in days when skiing would be possible based on the predetermined minimum snow depth criteria. This sample ski season is compared to actual average ski season length for the case studies. If there are discrepancies between modeled season length and historical averages minor alterations can be made to the snowfall and snowmelt parameters until season length is accurately reflected. Once this is completed the final test is to model a ski season using the LARS-WG synthetic baseline data. This step, along with all future modeling, uses the same parameters for snowfall and snowmelt determined through the calibration and validation phase. Upon successful ski season length modeling, SkiSim 2 is determined to be capable of modeling future changes to season length and snowmaking requirements.

The next stage in the modeling process is to project future impacts to season length and snowmaking at each site using the weather data for the 2050s climate change scenarios and downscaled with LARS-WG. All other parameters in the model (e.g. snowmaking capacity, decision rules for snowmaking) are assumed to remain constant and thus applied to the site-specific climate change scenarios. Once the future climate scenarios have been modeled for snowfall and snow melt, SkiSim concludes by modeling future season length and snowmaking requirements for each ski area individually, providing results in 100m bands.

Ski Operations Indicators Assessed

To determine the plausibility of 2050s ski operations under climate change, a range of outputs will be assessed to determine the potential impacts from climate change. The first indicator assessed is the 100-days rule, which will be used due to the precedent set in previous vulnerability assessments (Konig & Abegg 1997, Scott et. al. 2008b, Steiger 2010, 2011). This indicator provides insight into the potential for ski areas to maintain profits under scenarios of climate change (Konig & Abegg 1997, Scott et. al. 2008b, Steiger 2010, 2011).

The probability of remaining operable during the Christmas/New years segment will also be used for determining ski industry viability in Colorado and California by the 2050s. The Christmas/New Years segment accounts for the vast majority of visitation and is thus a large determinant of seasonal economic success (Scott et. al. 2003; Scott et. al. 2007). Scott et. al. (2008b) identify the ability to remain open in at least 75% of all years in the 30-year period as a pertinent economic indicator of ski industry viability under future warming.

Reductions to total season length provide a general outlook for the future of the ski industry under climate change scenarios, but it is critical to breakdown the season into individual segments for a more detailed economic assessment. Within SkiSim 2, the season is segmented by date into the following periods; the early season (Nov. 1-Dec. 21), the Christmas/New Years period (Dec. 22-Jan 4), the mid-season (Jan. 5-Feb. 8), the school holiday period (Feb. 9-Mar. 1), March (Mar. 2-Mar. 31), and April (Apr. 1-Apr. 30). SkiSim 2 also provides aggregate outputs of these segments classified as either the ‘low season’ or ‘high season’. The low season accounts for the early season and April segments, while the high season includes the Christmas/New Years period, the mid-season, the school holiday period and March segments. Reductions to skiable days throughout these aggregate segments will have varying impacts on future ski industry viability, as reductions to the high season are more likely to have a substantial impact on ski areas’ financial bottom line, these differences will also be considered (Scott et. al. 2008b).

Lastly, SkiSim 2 provides two projections for future snowmaking; one mimics typical snowmaking operations in practice, the other projects the volume of artificial snow required to maintain a period analogous to the high season (Figure 4.3).

The first projection (PROD_SNOW), measures the amount of snow that could, and would be needed to be produced to establish and then maintain at least the required minimum snow depth (30 cm) until April 15. In SkiSim 2, for PROD_SNOW, snowmaking assumes current technological capacity persists, while operations were prescribed to commence November 1 - or the first day following this date that temperatures permit it - and conclude April 15. In this output, artificial snow is produced at the beginning of the season until a critical snow depth threshold is reached. This threshold is defined as the combined (natural and artificial) snow depth required in maintaining at least 30 cm until April 15, in 90% of all years, considering natural snowfall and snowmelt. Snowmaking operations under PROD_SNOW are terminated when either temperature is $>-5°C$ or the critical threshold is reached. The value reported is the quantity of snow that is produced on average in the 30-year period.

Since the critical threshold when PROD_SNOW terminates varies according to natural snowfall and snowmelt, this output fluctuates extensively between ski areas, altitude and climate scenarios. Increases indicate that a larger portion of snow must be produced to maintain the snow base while climate conditions remain suitable to produce more snow. Decreases in PROD_SNOW indicate that climate conditions have become too warm to produce adequate artificial snow, resulting in a snow deficiency.

The second snowmaking output (REQ_SNOW) details how much artificial snow would be required to establish and maintain only the minimum (30 cm) snow depth for a 120 days season. For REQ_SNOW, temperature and technological thresholds are not considered, while snowmaking operations do not commence until December 15 and end April 15. Accordingly, REQ_SNOW is the amount of additional artificial snow that would be needed to supplement natural snow to supply a ski product throughout the high season only. It is a proxy of future snowmaking expansion, regardless of technological capacity.

Conclusion

As stated, the use of SkiSim 2, a semi-distributed ski operations simulation model, has been used in previous academic assessments to model historic season length and project impacts that result from climate change when snowmaking is fully accounted for. The climate stations selected and ski areas analyzed in this research have met numerous qualifications suggesting that SkiSim 2 is an appropriate tool in modeling future ski operations at these locations. The following chapter will discuss the results of this research.

4. Results

Introduction

The results from the SkiSim 2 model are outlined for each ski area. Preceding these results, the chapter begins by outlining the SkiSim 2 model validation results. The remainder of the chapter discusses the projected changes to ski season length, individual season segments, inter-seasonal reliability as well as snowmaking. Results are presented for each case study according to altitude, and are followed by summary findings for each ski area.

SkiSim 2 Model Validation Performance

Prior to running any future projections of ski operations under a climatically changed future it was necessary to ensure SkiSim 2 modeled current ski operations successfully. The results presented below are derived from the Validation phase of SkiSim 2's modeling process, outlined in the Methods chapter. The model validation compares the number of snow and skiable days generated in SkiSim 2 from historical weather data (referred to as 'measured days') to the number of snow and skiable days generated in SkiSim 2 with data from LARS-WG (referred to as 'modeled days'). For this comparison, snow days are defined as having precipitation with temperatures below 0°C, while a skiable day is defined by having 30 cm or greater snowpack. These definitions are consistent with previous assessments (Scott et. al. 2003, 2006, 2007, 2008, Steiger 2010).

For each climate station, SkiSim 2 was able to model snow and skiable days successfully. For the Tahoe City climate station within SkiSim 2, 137 annual measured days with snowfall were recorded, while there was 137 annual modeled days with snowfall, showing with no difference. Furthermore, SkiSim 2 measured 103 skiable days and modeled 104 skiable days (+1%). These figures indicate that SkiSim 2 could reproduce conditions at this climate station very well using LARS-WG data.

At the Vail climate station SkiSim 2 measured 188 days with snowfall, while modeling 172 (-8% difference). It measured 132 skiable days while modeling 117 (-11% difference). The increased average elevation of mountains, and more complex terrain, in the Colorado Rockies is likely to explain the larger differences between observed and modeled snowpack. This topographic feature results in a higher occurrence of microclimates being present and adversely affects SkiSim 2's ability to model the individual ski areas.

In addition to these comparisons, SkiSim 2 modeled baseline ski season length well for each case study ski area. For Squaw Valley, along with the broader Lake Tahoe ski region, the ski season typically commences in late November operating to the middle or end of April, resulting in season lengths of approximately 150 days (skilaketahoe.com 2011, NSAA 2011a). When averaged across all assessed elevations of Squaw Valley, SkiSim 2 modeled a 138 days (-8%) natural baseline season, with snowmaking included SkiSim 2 modeled a 153 days (+2%) baseline ski season.

For Colorado, both case studies report average seasons from mid-November to mid-April, again resulting in season lengths of approximately 150 days (Vail Resorts Management Company 2011). For Vail ski area, when averaged across all analyzed elevations, SkiSim 2 modeled a natural season length of 145 days (-3%) and a snowmaking inclusive season length of 171 days (+14%). While for Copper Mountain, SkiSim 2 modeled a natural season length of 159 days (+6%), extending to 173 days (+15%) when snowmaking is included. The above-average season length modeled with snowmaking for these two sites is explained through their lower proportional area of terrain currently equipped with snowmaking.

Projected Ski Operations Under Climate Change

Table 4.5 summarizes all ski season length projections for each case study. These findings, as well as projections of snowmaking, are further discussed for each ski area organized according to altitude. An overview of pertinent findings is also provided for each case study.

Table 4.1: Modeled Ski Season Length At All Study Areas

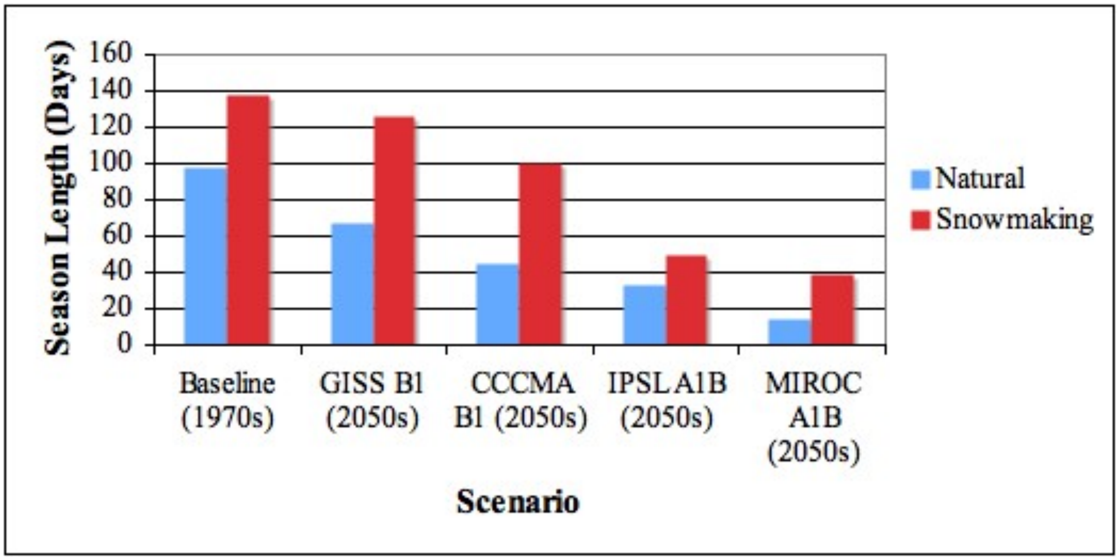
Ski Area	Altitude	Condition	1970s Season Length (Day)	2050s CCCMA B1 (%)	2050s GISS B1 (%)	2050s IPSL A1B (%)	2050s MIROC A1B (%)
Squaw Valley	Minimum	Natural	98	-55	-31	-67	-85
		Snowmaking	137	-27	-8	-64	-72
	Mean	Natural	152	-15	-7	-27	-43
		Snowmaking	154	-6	-2	-13	-16
	Maximum	Natural	165	-3	-2	-6	-6
		Snowmaking	168	-4	-2	-8	-8
Vail	Minimum	Natural	127	-8	-4	-36	-35
		Snowmaking	169	-5	-1	-19	-18
	Mean	Natural	148	-2	2	-18	-21
		Snowmaking	171	-2	0	-7	-7
	Maximum	Natural	161	0	1	-9	-13
		Snowmaking	174	-1	0	-4	-5
Copper Mountain	Minimum	Natural	148	-2	2	-18	-21
		Snowmaking	171	-2	0	-7	-7
	Mean	Natural	158	0	2	-9	-13
		Snowmaking	174	-1	0	-5	-5
	Maximum	Natural	171	-3	-2	-9	-14
		Snowmaking	175	-1	0	-3	-4

Squaw Valley (California)

Minimum Altitude (1900m)

Projections for ski season changes and snowmaking requirements are most pronounced at this elevation. In comparing natural skiable days with skiable days inclusive of snowmaking, the influence of a warmer climate and the importance of snowmaking as an adaptation strategy are evident. Figure 4.1 displays the efficacy of snowmaking in extending season length in the baseline period as well as under climate change scenarios.

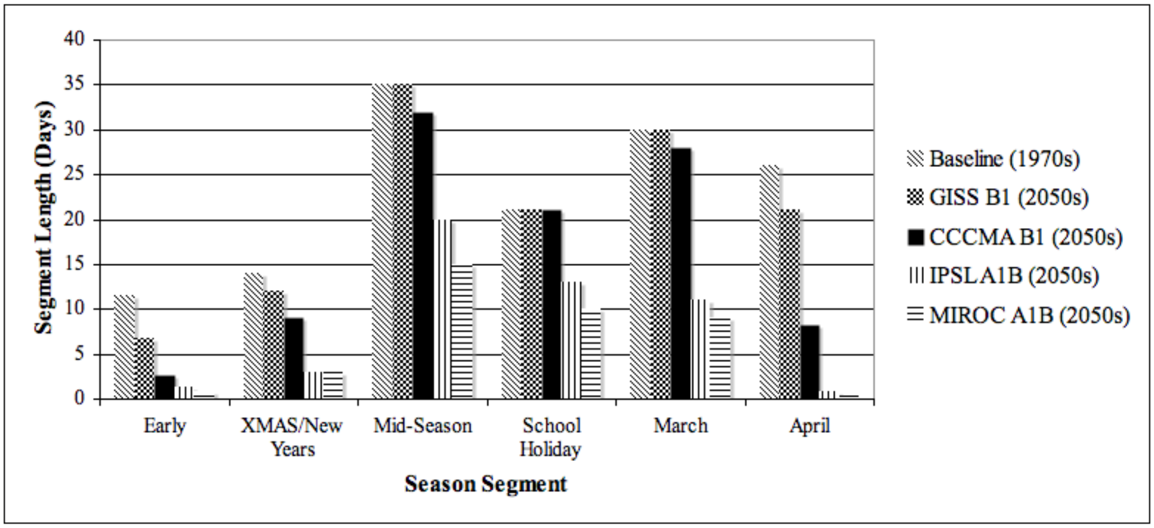
Figure 4.1: Squaw Valley Minimum Altitude Ski Season Length



SkiSim 2 modeled 98 skiable days, without snowmaking, at this elevation in the baseline scenario. A warmer climate would have adverse impacts on natural season length at this elevation. Natural season length is reduced by 31 days (-31%) (GISS B1), 54 days (-55%) (CCCMA B1), 65 days (-64%) (IPSL A1B) and 84 days (-72%) (MIROC A1B). When snowmaking is included, the baseline scenario was modeled at 137 skiable days, a 40% increase over natural baseline season length. Relative to this scenario, projections for the 2050s under the four future change scenarios reduce skiable days by 11 (-8%) (GISS B1), 37 (-27%) (CCCMA B1), 88 (-64%) (IPSL A1B) and 98 (-72%) (MIROC A1B). Clearly, increased temperatures would impact season length regardless of snowmaking capacity, however, snowmaking sustains a larger portion of skiable days than natural conditions alone. An important projection is that with snowmaking under the B1 emission scenarios, ski season length can be maintained above 100 days, a level that suggests ski areas will remain profitable.

Reductions to total season length provide a general outlook for the future of the ski industry under climate change scenarios, but it is critical to breakdown the season into individual segments for a more detailed economic assessment. Figure 4.2 displays lost skiable days during each segment under future 2050s climate scenarios.

Figure 4.2: Squaw Valley Minimum Altitude Season Segment Length



These projections suggest that in the future operations will need to intensify during the high season to reduce potential lost revenues in the early season and April. This is particularly true for the A1B scenarios where impacts are projected to be most severe. Ski operators will need to plan on intensifying operations from the mid-season through March, especially if warmer scenarios occur since the Christmas/New Years period has significant impacts.

In the baseline scenario with snowmaking, there are 38 total low season skiable days. Low season days suitable for skiing is reduced to 28 days (GISS B1), 11 days (CCCMA B1), 2 days (IPSL A1B) and 1 day (MIROC A1B) by the 2050s. Under the 'least change' scenarios these impacts are more pronounced in the early season, with a 77% reduction (CCCMA B1) and 41% reduction (GISS B1). However, in the CCCMA B1 2050s scenario, substantial reductions (-18 days) are also projected for April at this elevation. Under the 'most change' 2050s scenarios projected impacts are drastic for both the early season and April segments. In the early season, losses amount to 88% (IPSL A1B) and 92% (MIROC A1B), while in April skiable days are reduced by 97% (IPSL A1B) and 99% (MIROC A1B).

The high season is not as affected by a warming climate, despite being significantly reduced under the two 'most change' projections. In the baseline scenario with snowmaking, SkiSim 2 modeled the high season at the total amount possible; 100 skiable days. Under the four future change scenarios, this season segment is reduced to

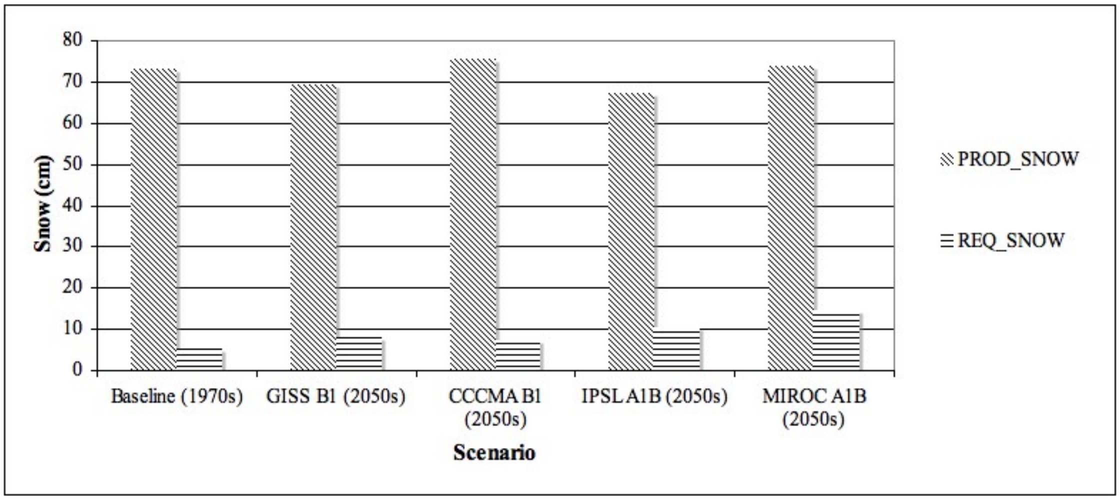
98 skiable days (GISS B1), 90 skiable days (CCCMA B1), 47 skiable days (IPSL A1B) and 37 skiable days (MIROC A1B). The A1B emission scenario's mid-season losses account for an additional 15 and 20 skiable days lost, this compares to 0 (GISS) and 3 (CCCMA) skiable days lost during the mid-season in the B1 scenarios.

The probability of remaining open throughout the Christmas/New Years period during the 2050s (2040-2069) is the second economic indicator assessed. In the baseline scenario, inclusive of snowmaking, Squaw Valley's minimum elevation was modeled to be open for only 90% of the time. Projections for the 2050s, also inclusive of snowmaking, show that 80% of the years under the GISS B1 scenario will remain open, while only 10% of the years under the IPSL A1B and MIROC A1B scenarios. This reduction would have serious implications on the future of the ski industry in a warmer climate at this altitude.

In the baseline scenario 85.3 cm of snow was produced (PROD_SNOW) to supply a 137 days ski season. Under the B1 scenarios snow production could be increased by 10% (+9 cm) (GISS B1) and 1% (+1 cm) (CCCMA B1), however, season length still decreases. The two 'most change' 2050s scenarios project decreases to snow production, being reduced by 21.1% (-18 cm) (MIROC A1B) and 26.3% (-22 cm) (IPSL A1B) (Figure 4.3). These latter two scenarios will result in a snow deficit that further jeopardizes operations, as displayed through the larger reductions to ski season length.

When considering the second snowmaking output (REQ_SNOW) provided by SkiSim, the sustainability of this strategy is jeopardized. To maintain the minimum operable snow base throughout only the December 15 to April 15 period, 50.2 cm of artificial snow was required in the baseline scenario. In consideration of future climate change scenarios, artificial snowmaking must increase by 28 cm (55.5%) (GISS B1), 122 cm (244%) (IPSL A1B) and 141 cm (281%) (MIROC A1B) (Figure 4.3). Scenarios where PROD_SNOW exceeds REQ_SNOW, such as IPSL A1B and MIROC A1B, demonstrate that snowmaking may not be a sufficient adaptation strategy to climate change as temperatures are likely to become too warm for snowmaking.

Figure 4.3: Squaw Valley Minimum Altitude Snowmaking

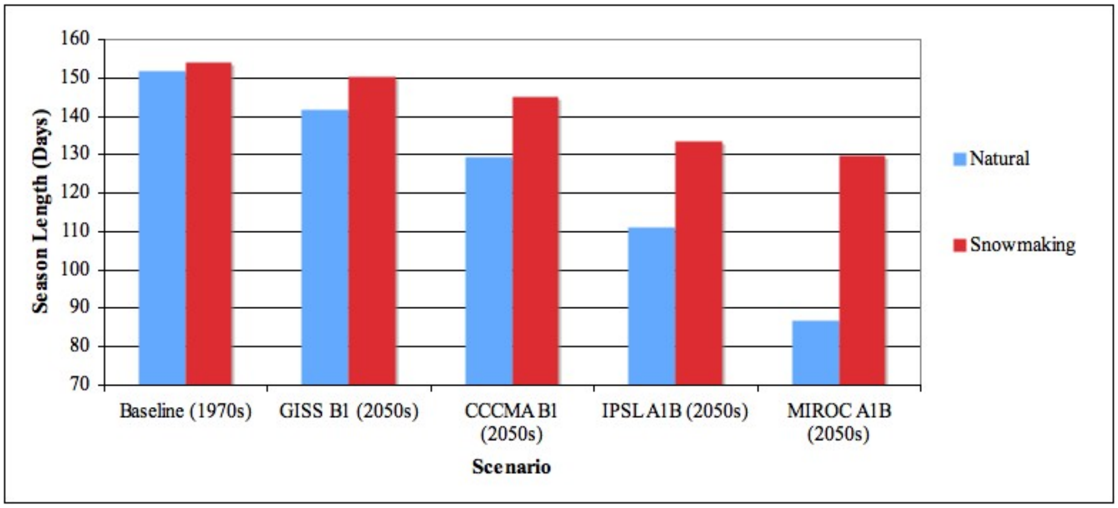


Mean Altitude (2350m)

Projections of climate change impacts on ski operations at this elevation are more limited relative to the minimum altitude of 1900 masl. This displays the importance of elevation for ski operations, especially under warming climate conditions. SkiSim 2 modeled the natural ski season length at 152 days in the baseline scenario, which is reduced by 10 days (GISS B1) and 22 days (CCCMA B1) in the 'least change' scenarios. Under the two A1B scenarios, natural season length is reduced more significantly, losing 41 days (IPSL A1B) and 65 days (MIROC A1B). These figures are more encouraging than at the minimum elevation, since in 75% of the scenarios ski operations are able to maintain the 100-day rule (Figure 4.4).

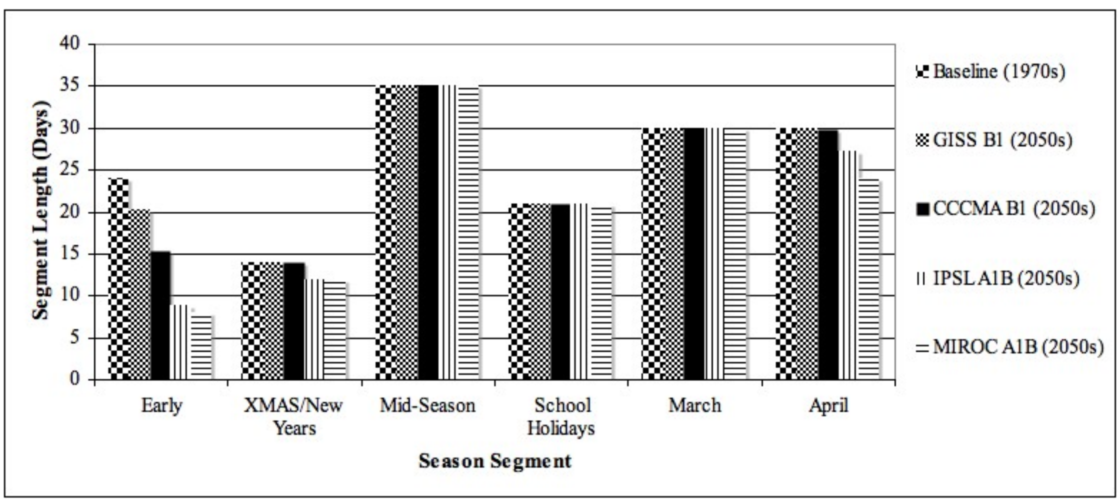
At this elevation the efficacy of snowmaking in maintaining baseline season length under future climate scenarios is more pronounced than at the minimum elevation (Figure 4.4). The 100-day rule is exceeded at this elevation in all future scenarios with snowmaking included. Baseline season length inclusive of snowmaking was modeled at 154 skiable days at this elevation. Under the four climate scenarios it is reduced by 4 days (GISS B1), 9 days (CCCMA B1) 21 days (IPSL A1B) and 24 days (MIROC A1B).

Figure 4.4: Squaw Valley Mean Altitude Ski Season Length



The reduction in season length at this elevation follows a similar pattern as the minimum elevation with regards to the high and low season segments (Figure 4.5). The majority of losses are expected during the latter segment, as was the case at the lower altitude. Low season losses primarily occur in the early season and range between 4 and 16 days, this compares to 3 to 6 days lost in April.

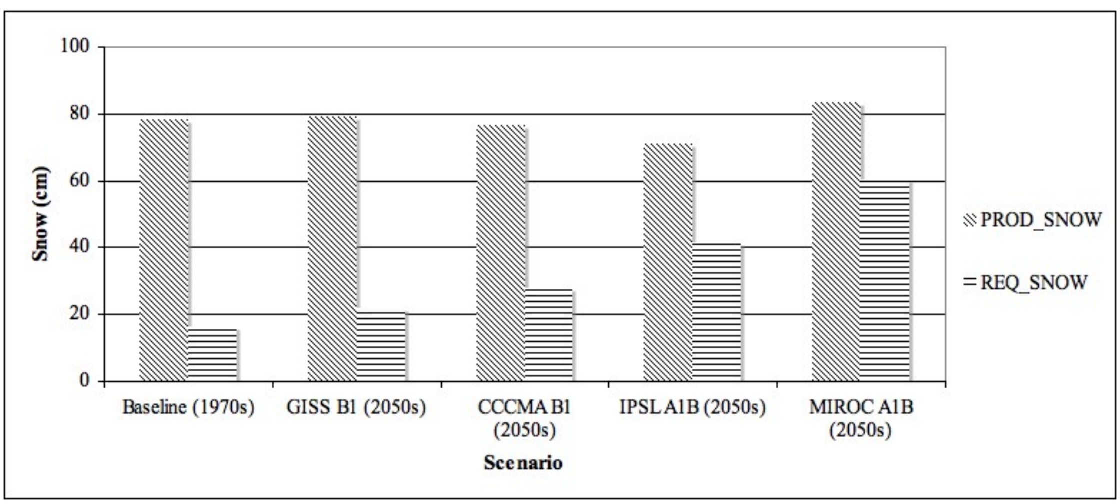
Figure 4.5: Squaw Valley Mean Altitude Season Segment Length



The high season is modeled at the maximum 100 days in the baseline scenario. While this is maintained in both B1 scenarios, under the A1B scenarios ski areas will lose a small portion of their prime high season revenue generating days. A discerning facet of these reductions is that they are projected to occur during the Christmas/New Years segment. As discussed above, successful operations during this portion of the season are critical to profits (Scott et. al. 2003; Scott et. al. 2007). While a reduction of 2 days (IPSL A1B, MIROC A1B) is unlikely to result in major disruptions to seasonal revenues, the change percentage of seasons with a fully operational Christmas/New Years segment is substantial. SkiSim 2 modeled only 76% (IPSL A1B) and 72% (MIROC A1B) of all years during the 2050s as having this segment fully operational. The 'most change' projections still threaten future industry revenues and viability at this altitude. These projections are more concerning than reductions to modeled skiable days for this segment, as they better account for inter-seasonal reliability and sustained revenues.

Changes in PROD_SNOW and REQ_SNOW under future change conditions at this altitude are also more limited. PROD_SNOW in the baseline scenario was modeled at 78 cm and fluctuated greatly under the four future climate scenarios. It increased to 79 cm (+1%) (GISS B1) and 83 cm (+6%) (MIROC A1B) in scenarios with reductions to precipitation (both annual and winter), while decreasing to 76 cm (-3%) (CCCMA B1) and 71 cm (-10%) (IPSL A1B) in scenarios where winter precipitation increases. In the latter two scenarios it is likely that the projected increases in winter precipitation, combined with projected temperature increases, result in a higher level of humidity and occurrence of events where precipitation falls as rainfall. Such events limit the ability to create artificial snow since cooler temperatures are required for snowmaking when humidity is elevated (Steiger & Mayer 2008).

Figure 4.6: Squaw Valley Mean Altitude Snowmaking

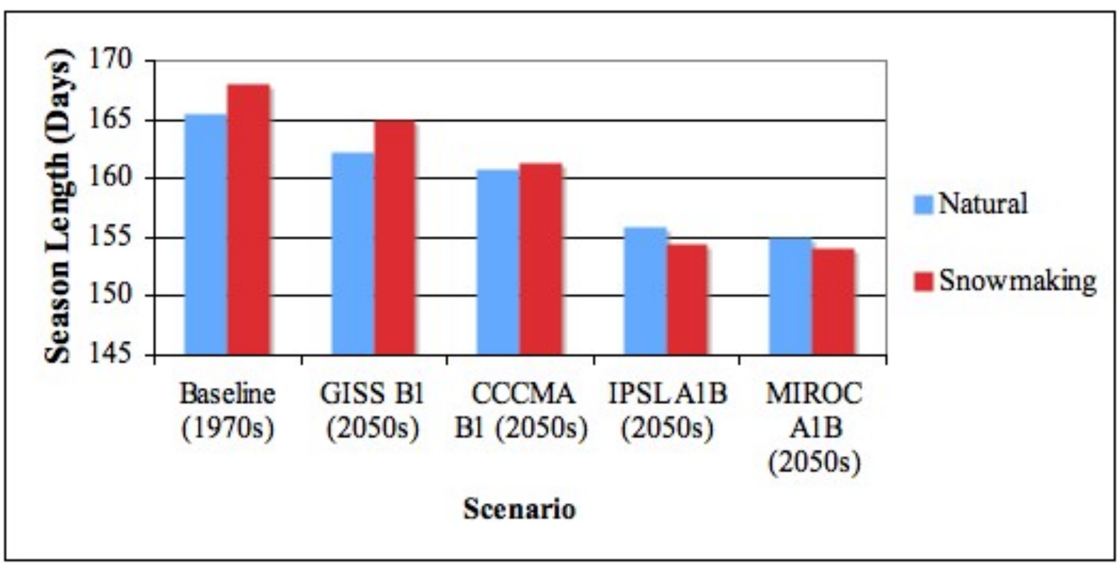


Similar to the minimum elevation, REQ_SNOW increases relative to the baseline period in all future climate scenarios. To maintain a 30 cm snow depth between December 15 and April 15 in the baseline scenario, 16 cm of artificial snow is required. Snowmaking requirements increase by 6 cm (GISS B1) and 12 cm (CCCMA B1) in the B1 2050s projections and by 25 cm (IPSL A1B) and 44 cm (MIROC A1B) in the A1B 2050s scenarios. An important projection at this elevation is that the ability to produce artificial snow under current technological capacity exceeds requirements under all future scenarios. Despite increases to REQ_SNOW, snowmaking will remain a plausible adaptation strategy at this altitude. This is significant as snow production at this altitude may serve to reduce the vulnerability of lower altitude operations to climate change. The lower altitude's inadequate snow production could be compensated by snow production at the higher altitudes, with snow being transported to lower sections of the ski area to sustain a larger portion of total skiable terrain.

Maximum Altitude (2800m)

Ski operations at this altitude have the least impacts projected for Squaw Valley. The outlook further emphasizes the importance of elevation in sustaining ski operations under warmer climate conditions. Figure 4.7 displays season length projections for both natural skiable days and skiable days inclusive of snowmaking

Figure 4.7: Squaw Valley Maximum Altitude Ski Season Length



Skiable days during the baseline period, under natural conditions, at the maximum altitude were modeled at 165 and increase only slightly to 168 when inclusive of snowmaking. Natural skiable days under the four 2050s climate change scenarios are also maintained >100 days for Squaw Valley; 162 days (GISS B1) 155 days (MIROC A1B) and 156 days (IPSL A1B). These are particularly promising projections, as in each scenario natural conditions alone will suffice in upholding the 100-day rule. This suggests that this ski area's operations could remain profitable at this high altitude.

As mentioned, snowmaking only slightly increased baseline season length at this altitude, as it is not needed. An interesting finding for Squaw Valley at this altitude, is that under the 2050s climate scenarios total skiable days and reductions in skiable days from the baseline period are consistent between projections inclusive and exclusive of snowmaking. Under GISS B1 2050s conditions, when inclusive of snowmaking, skiable days were modeled at 165 (GISS B1), just 3 days more than natural conditions alone under the same climate scenario. However, relative to the baseline period the number of skiable days will be reduced by 3 in scenarios that are both inclusive and exclusive of snowmaking. This can be explained through the aforementioned consideration that at this altitude natural conditions alone will suffice in supplying an adequate ski product and season length. As exemplified in the baseline scenario, climate conditions only allow for a season length of certain duration, even if artificial snow production was employed it would only extend season length marginally.

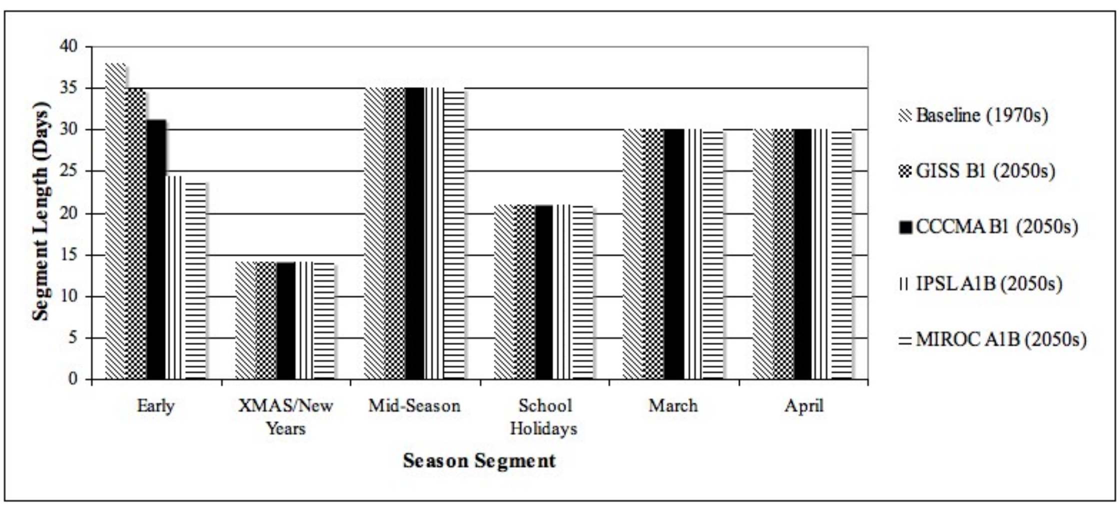
Two surprising projections were the number of skiable days under the two 'most change' scenarios at this elevation, as season length inclusive of snowmaking is less than without snowmaking. This can be explained through annual climate variability within the LARS-WG data and the reduced impact of snowmaking on ski season length. The differences between these scenarios (with or without snowmaking) are effectively no change. This is best evidenced by the fact that in the baseline scenario, including snowmaking in projections only increases season length by 1%, likewise when snowmaking is included in future A1B climate change projections, the difference in ski season length is 1%.

Figure 4.8 demonstrates the unequal distribution of lost skiable days between the high and low season segments during the 2050s for Squaw Valley's maximum altitude.

Continuing the trend from lower altitudes, all reductions to season length occur during the low season, which is projected to provide 68 skiable days in the baseline scenario. This segment will be reduced to 65 days (GISS B1) and 54 days (IPSL A1B and MIROC A1B) when inclusive of snowmaking. A unique projection for losses at this elevation is the distinction that losses only occur in the early season. Both lower elevations examined had lost skiable days in April also. Furthermore, an additional distinctive finding is that the Christmas/New Years period will be sustained throughout 100% of the years during the 2050s at this altitude.

Together these projections are very promising for Squaw Valley and other high altitude ski areas in the Lake Tahoe region. These projections indicate that at this altitude operations will not only exceed the 100-day rule but ski areas will be able to remain open during key season segments allowing for maximum revenue generation. Furthermore, the ability to provide such extensive operations at this altitude increases the resilience of lower altitude operations. The most likely result is the overall maintenance of earnings. While these earnings will suffer from the additional costs of snowmaking expansion and increased energy use, those generated through sustained operations at high altitudes could overcome losses from reduced season length at lower altitudes.

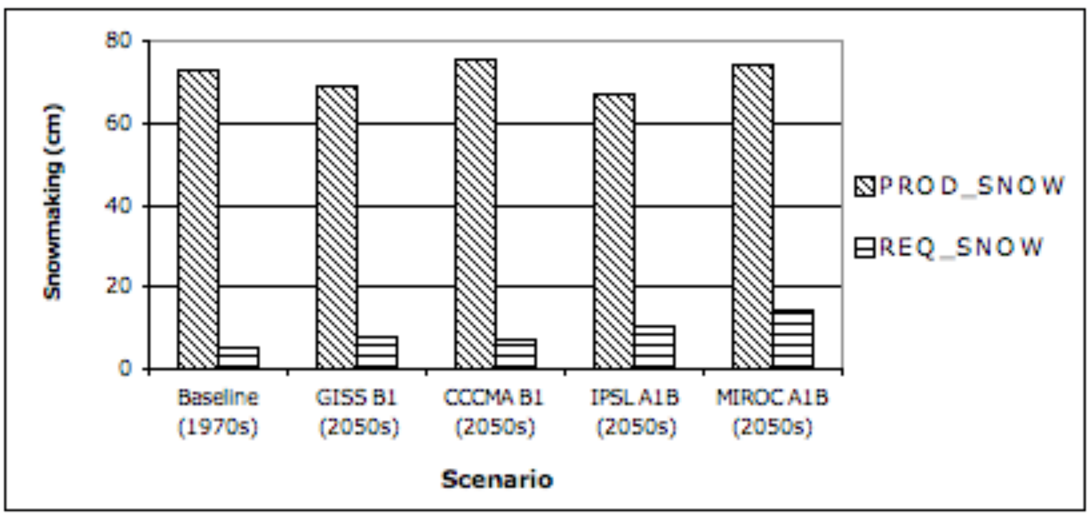
Figure 4.8: Squaw Valley Maximum Altitude Season Segment Length



PROD_SNOW and REQ_SNOW again have more limited adverse impacts projected relative to the lower elevation operations. In the baseline scenario, SkiSim 2 findings indicate that 73 cm of artificial snow could be produced to establish the critical threshold in maintaining at least the 30 cm minimum until April 15. This increases to 76 cm (GISS B1) and 74 cm (MIROC A1B) in the scenarios with reduced precipitation, while decreasing to 69 cm (CCCMA B1) and 67 cm (IPSL A1B) in the scenarios with increased winter precipitation (Figure 4.9). SkiSim 2 modeled REQ_SNOW at this elevation in the baseline scenario at 5 cm, increasing under all of the 2050s climate change scenarios. Consistent with trends from the two lower elevations, the least change is anticipated in the GISS B1 (+2 cm) scenario, while REQ_SNOW increases by 5 cm (IPSL A1B) and 10 cm (MIROC A1B) under the 'most change' scenarios.

Since artificial snow production under technological constraints exceeds potential requirements, snowmaking is likely to remain a sufficient adaptation strategy. Similar to mean altitude, snowmaking production at this altitude can be used to offset decreased snowpack and snowmaking potential at the lowest elevation, increasing the resilience of the entire ski area.

Figure 4.9: Squaw Valley Maximum Altitude Snowmaking



Squaw Valley Overview

Overall, projections for Squaw Valley ski area in California's Lake Tahoe ski region do not predict a favourable future for ski operations under a warming climate. The most important finding is the more limited impact at higher elevations, as nearly all variables analyzed forecast more favourable futures at higher altitudes; those that do not are projected as no change between the ski area's altitudinal range. When comparing the lowest and highest altitudes, baseline ski season length is 68% (without snowmaking) and 23% (with snowmaking) longer at the highest altitude. The influence of altitude on ski season is best displayed under the future climate change scenarios. When averaged across the four climate change scenarios, ski season length is 399% (without snowmaking) and 202% (with snowmaking) longer at the highest altitude than the lowest altitude (Figure 4.10).

In addition to reductions to total skiable days, lower altitude operations are projected to have higher reductions in key season segments. This includes the Christmas/New Years period, which is likely to impact profitability to a large degree. Figure 4.11, Figure 4.12 & Figure 4.13 exhibit the relationships between altitude and season segment duration.

Figure 4.10: Squaw Valley Ski Season Length (With Snowmaking)

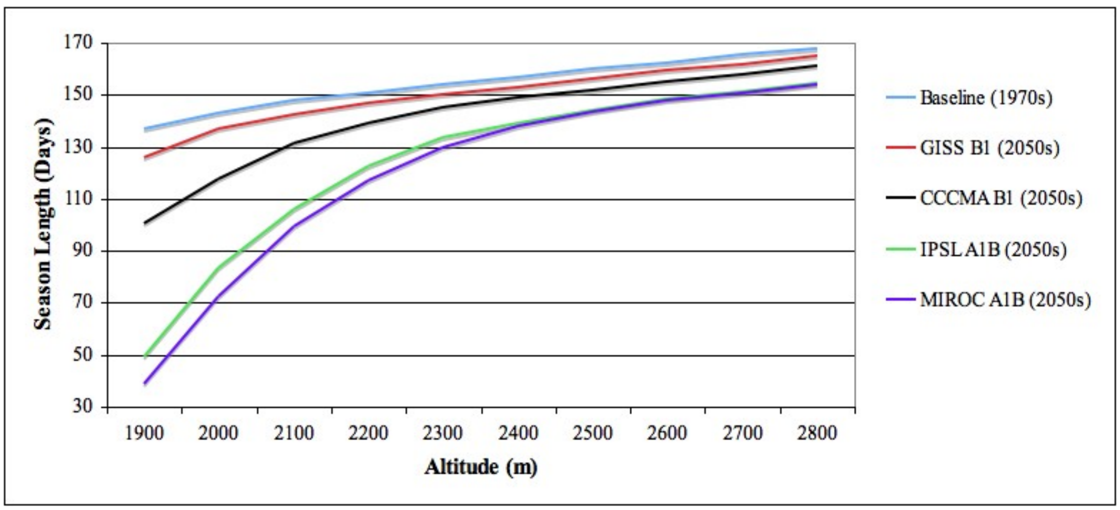


Figure 4.11: Squaw Valley Low Season Length (Nov. 1-Dec. 21, Apr. 1-Apr. 30)

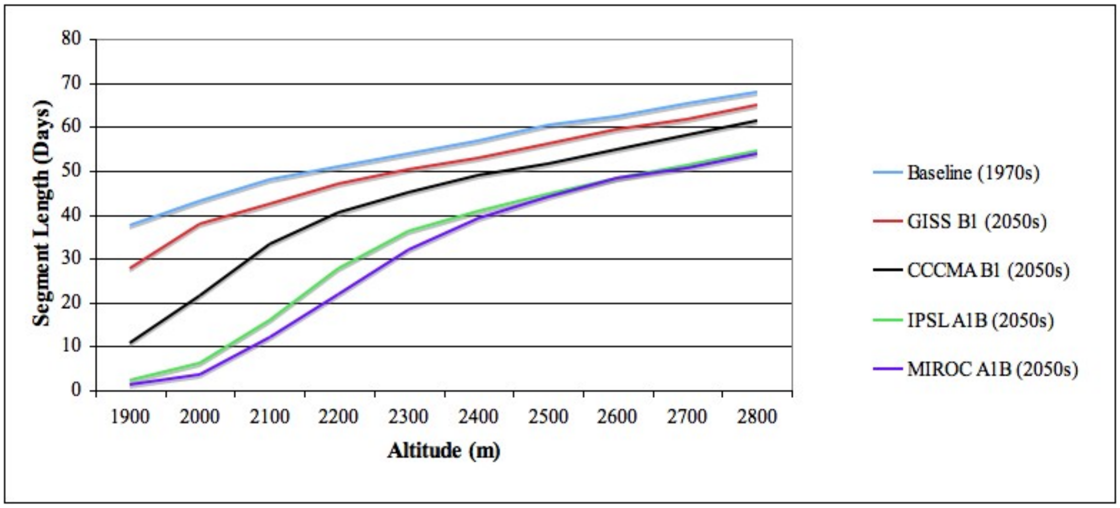


Figure 4.12: Squaw Valley High Season Length (Dec. 22-Mar. 31)

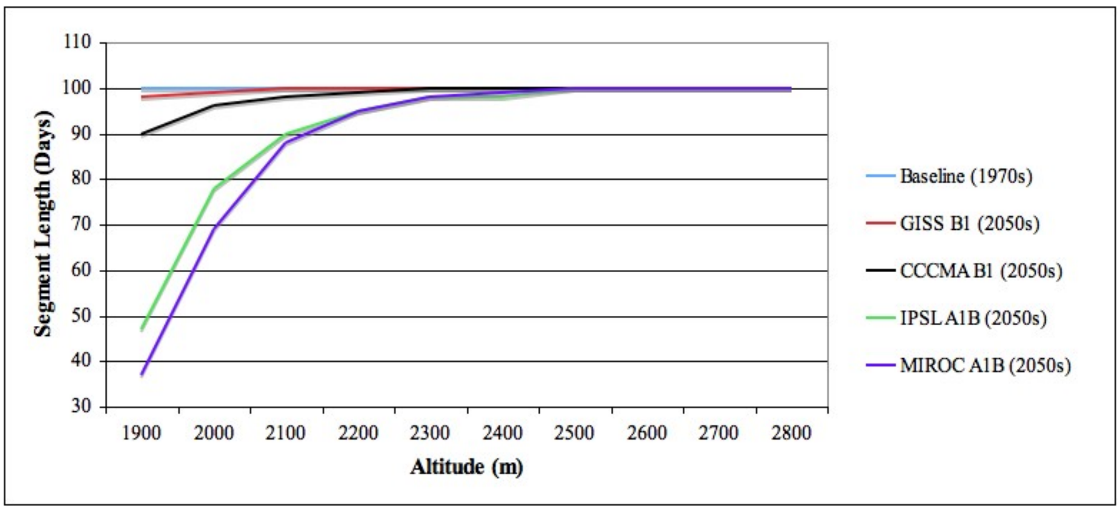
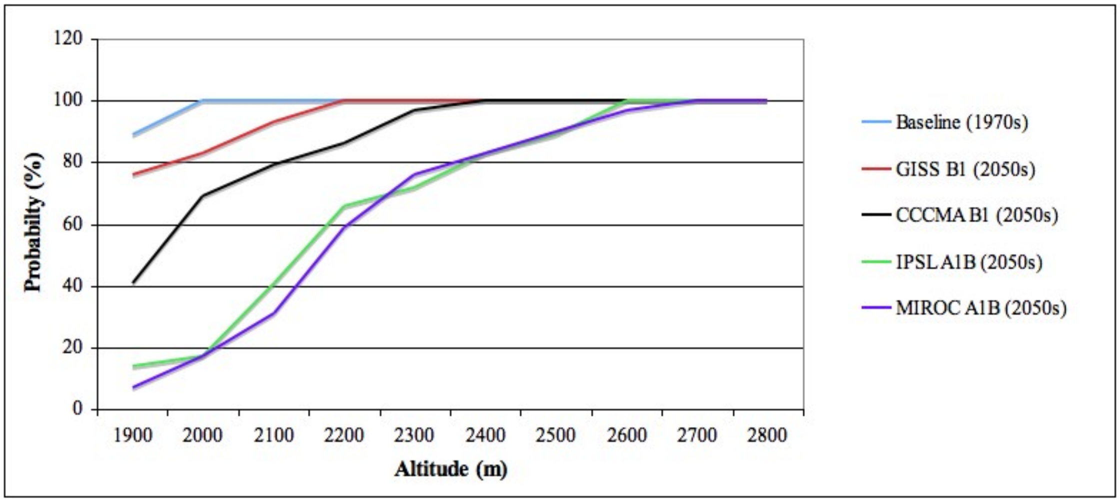


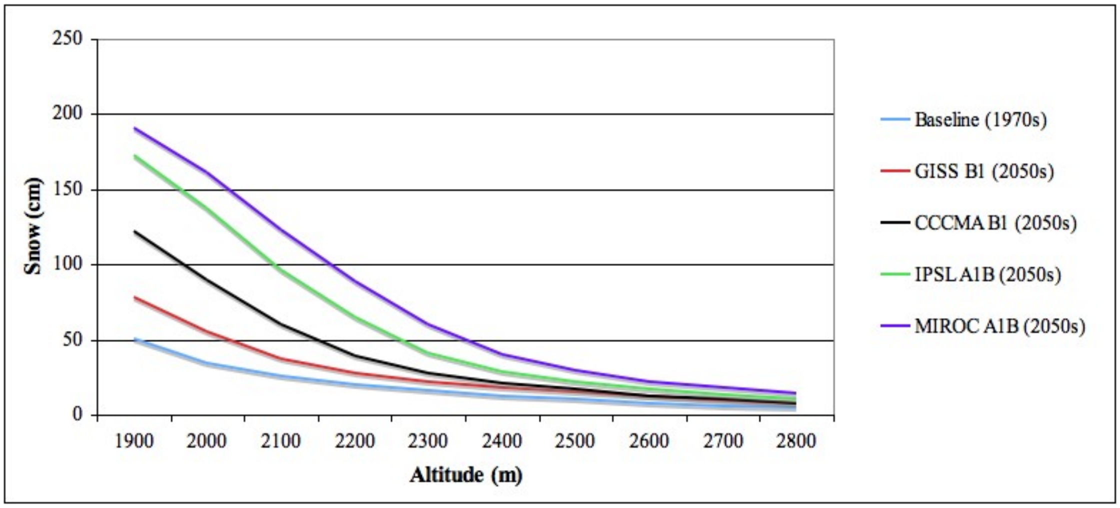
Figure 4.13: Squaw Valley Proportion of Years With an Operable Christmas/New Years Segment



Lastly, snowmaking has been shown to improve the outlook of future operations at the minimum and mean altitude as it sustains a larger proportion of skiable days into the future in comparison to natural conditions alone. However, its use may be limited at the minimum altitude as projected artificial snow requirements during the high season exceed potential production under current technological capacity. Conversely, at the highest altitude its impact on ski season length is negligible, as natural conditions will suffice in sustaining current average season length.

There is a clear relationship between altitude and REQ_SNOW, as with increasing elevation, the requirement for artificial snow in maintaining the minimum operable snow depth during key revenue generating season segments is decreased (Figure 4.14). This voids its reduced ability to extend and preserve season length at higher altitudes. Overall, snowmaking will be an invaluable adaptation strategy for ski area operators in this location. As discussed, artificial snow production will remain possible at higher altitudes, potentially compensating losses to production at lower altitudes, serving to increase the resilience of ski areas on the whole.

Figure 4.14: Squaw Valley Required Snowmaking



Copper Mountain (Colorado)

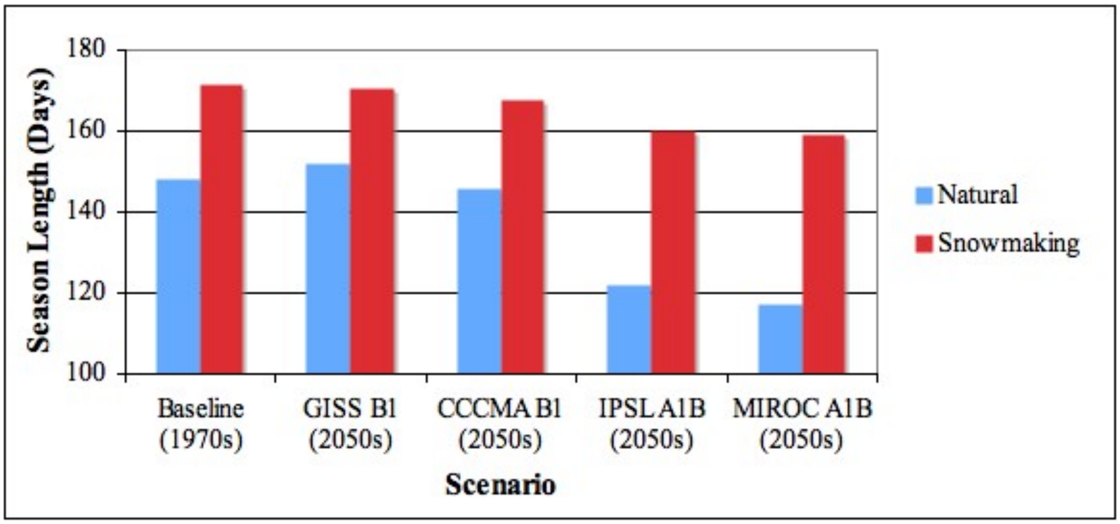
Minimum Altitude (3000m)

Projections for season length at this altitude of the Copper Mountain ski area vary according to the 2050s climate change scenarios. Baseline natural season length was modeled at 148 skiable days, it is reduced in three future scenarios to 146 days (CCCMA B1), 122 days (IPSL A1B) and 117 days (MIROC A1B). The number of skiable days increases by 2% (152 days) in the GISS B1 scenario, which is explained through increases in precipitation in November accompanied with minimal temperature increase, resulting in more snowfall (Table 4.4). However, as discussed for Squaw Valley's maximum altitude season length projections, changes of this magnitude are effectively deemed no change. In this scenario, along with others of similar magnitude (1-3%) potential future climate change is not projected to the extent that disruptions to ski season length will occur past current average climate variability.

At this altitude of Copper Mountain future natural climate conditions, exclusive of snowmaking, will suffice in sustaining an adequate season length (>100 days) into the 2050s. This is a promising finding as the minimum altitude has been repeatedly identified as most vulnerable to the impacts of climate change (Scott et. al. 2012b). Figure 4.15 displays season length and the impact of climate change at Copper Mountain's minimum altitude, including both natural and snowmaking inclusive projections.

When snowmaking is included, season length in the baseline scenario increases to 171 skiable days, a 16% increase above natural conditions. It is reduced in all future scenarios, with the B1 scenarios predictably having the least change at 170 skiable days (GISS B1) and 167 skiable days (CCCMA B1). The largest reductions occur in the A1B scenarios and result in season length being restricted to between159 (IPSL A1B) and 160 skiable days (MIROC A1B).

Figure 4.15: Copper Mountain Minimum Altitude Ski Season Length



When examining the timing of these reductions, a promising finding is that the majority of losses are projected to occur during the early season. This segment accounted for 41 days in the baseline scenario and is reduced to 40 days (GISS B1), 37 days (CCCMA B1), 30 days (IPSL A1B) and 29 days (MIROC A1B) (Figure 4.16). Only under the two 'most change' scenarios is a reduction in skiable days predicted for any other segment; such losses account for less than 1 day in April, rendering them negligible. Another important finding to note is the percentage of years likely to remain open during the Christmas/New Years period during the 2050s. This segment is sustained at 100% of all years during the 2050s, under all future climate change scenarios. Figure 4.16 displays the length of all season segments at this elevation, inclusive of snowmaking.

Together, these findings suggest that Copper Mountain will sustain a large portion of its revenue generating days throughout the ski season. When snowmaking is employed, operators will be able to sustain ski operations during the entire high season.

This is an important projection considering that the high season constitutes 100 skiable days allowing profits to be upheld at this ski area. Moreover, this is an especially encouraging finding since these projections denote the lowest elevation of Copper's operations. Areas at higher elevations will be even more likely to withstand projected climate change.

Figure 4.16: Copper Mountain Minimum Altitude Season Segment Length

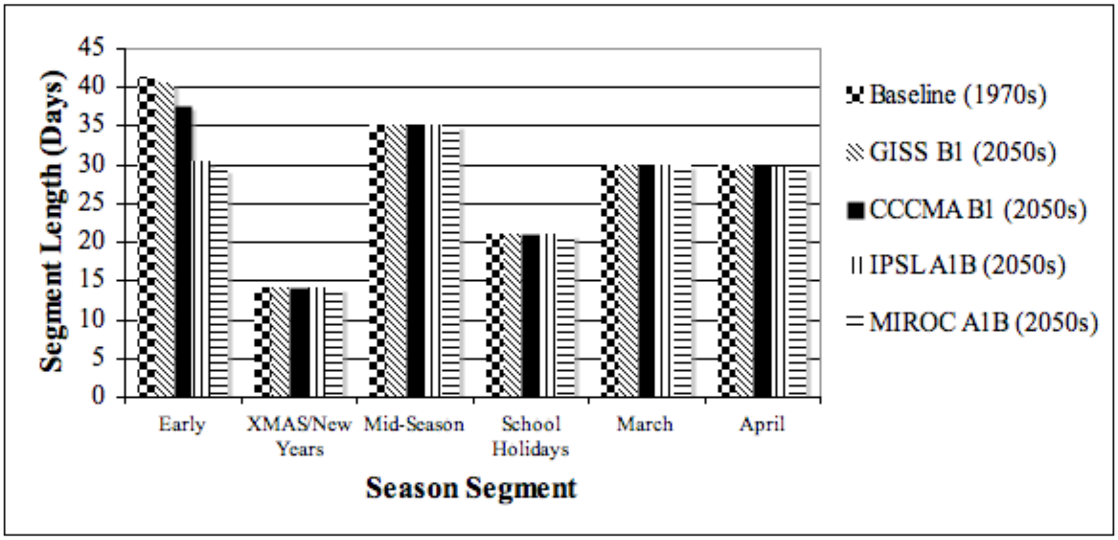
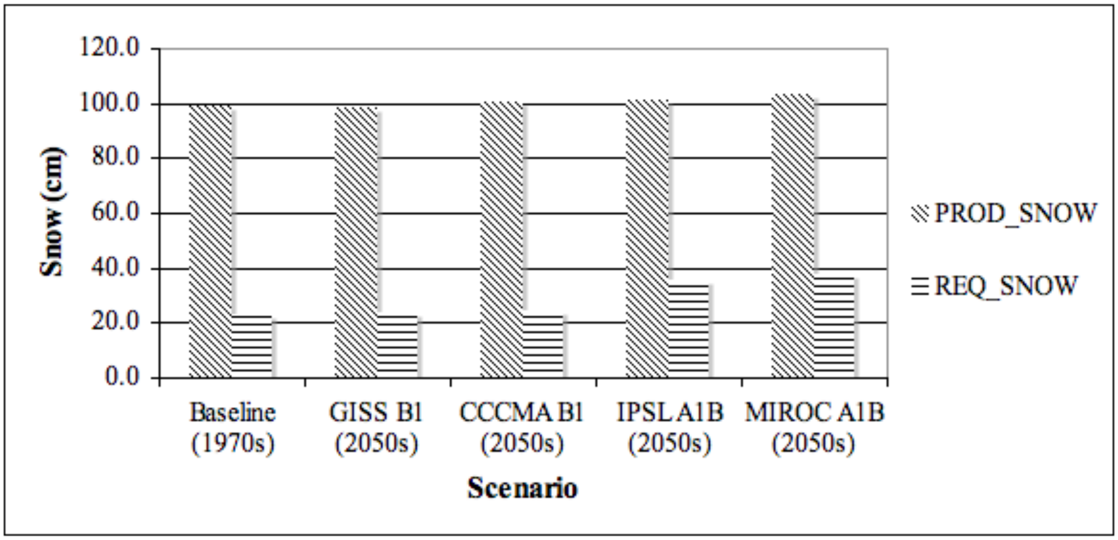


Figure 4.17 highlights the projections of artificial snowmaking production and requirements at this elevation for the 2050s. Projections of PROD_SNOW and REQ_SNOW at this altitude are greater than any other altitude of Copper Mountain. In the baseline scenario, SkiSim 2 findings indicate that 99 cm of snow was produced, under the defined capacities, to establish the critical threshold required in maintaining the minimum snowpack until April 15. Only under GISS B1 (-1%) conditions is there a reduction in potential production. Under the other three scenarios PROD_SNOW increases to 101 cm (CCCMA B1), 101 cm (IPSL A1B), and 103 cm (MIROC A1B) (Figure 4.17).

Snowmaking requirements at this altitude for the December 15 – April 15 period, during the 1970s, were modeled at 23 cm. As expected, changes to these requirements are least pronounced in the B1 scenarios, which require 24 cm (GISS) and 25 cm (CCCMA), while the A1B scenarios require 36 cm (ISPL A1B) and 38 cm (MIROC A1B) (Figure 4.17). Production throughout the season exceeds future requirements during the high season, which is an encouraging prospect that suggests snowmaking is likely to remain a viable adaptation strategy at Copper into the 2050s.

Figure 4.17: Copper Mountain Minimum Altitude Snowmaking



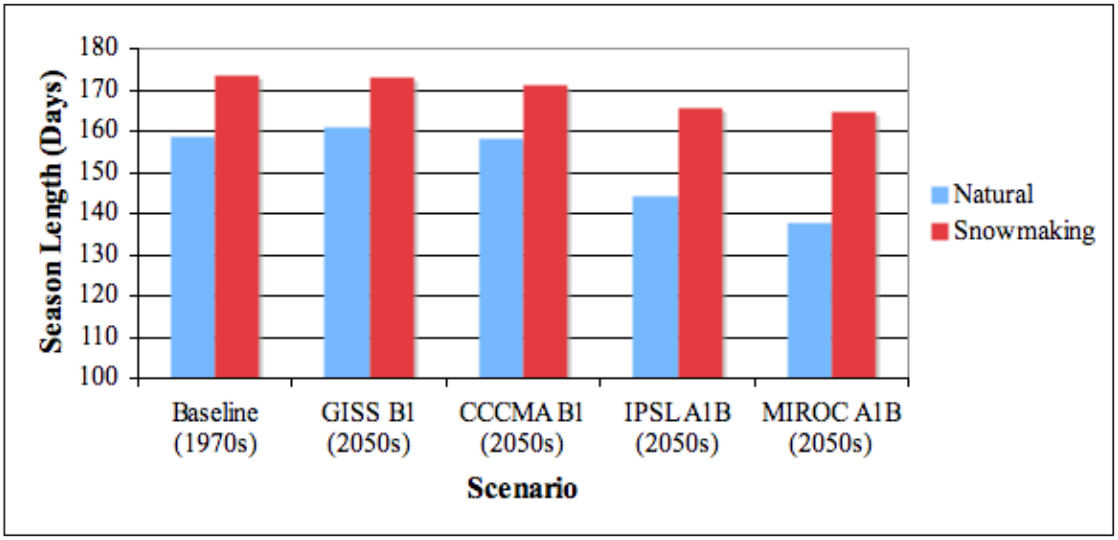
Mean Altitude (3400m)

Reductions to season length and changes in snowmaking improve relative to the minimum altitude. Natural season length was modeled at 158 days with minimal reductions under the ‘least change’ scenarios and moderate impacts under the ‘most change’ scenarios. SkiSim 2 modeled a season length (without snowmaking) of 161 skiable days in the GISS B1, a 2% increase over baseline season length. This is again explained through annual climate variability in the data set, as future climate change is not projected to be severe enough to disrupt ski season length in this scenario; this is a no change scenario. Under the CCCMA B1 scenario (158 days season) natural season length is maintained at the baseline length, while reductions occur under the IPSL A1B scenario (144 days season) and the MIROC A1B scenario (137 days season) (Figure 4.18).

When inclusive of snowmaking, future ski operations are more likely to be preserved. Baseline season length with 100% snowmaking was modeled at 174 days. This figure is reduced by 1 day (GISS B1) and 3 days (CCCMA B1) in the ‘least change’ scenarios. Impacts to season length under the ‘most change’ scenarios are more pronounced, however, snowmaking vastly improves these outlooks relative to natural season length (Figure 4.18). When inclusive of snowmaking, season length is reduced to

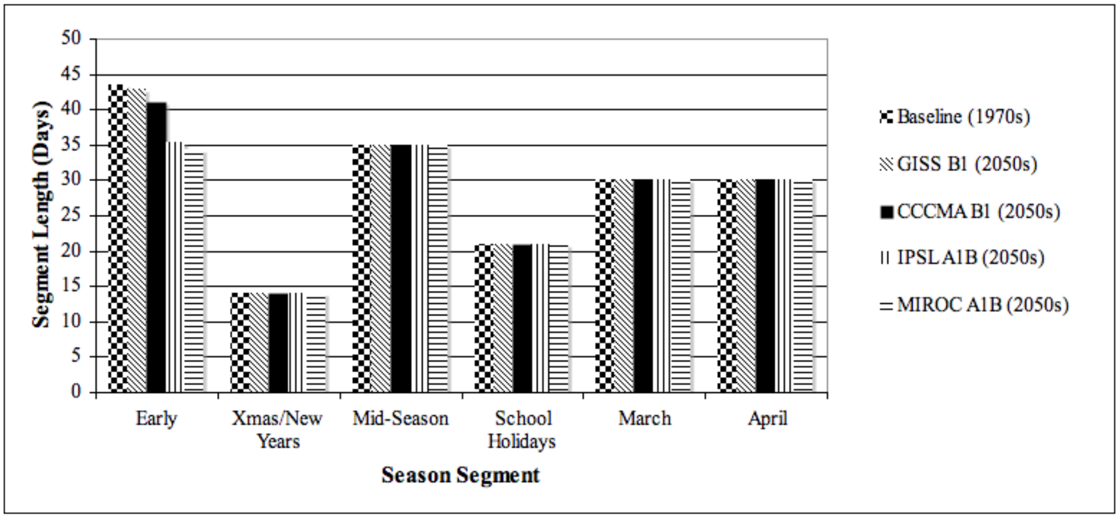
165 days (IPSL A1B) and 164 days (MIROC A1B). These 8 and 10 days reductions compare to 14 and 21 days lost in the same scenarios under natural conditions.

Figure 4.18: Copper Mountain Mean Altitude Ski Season Length



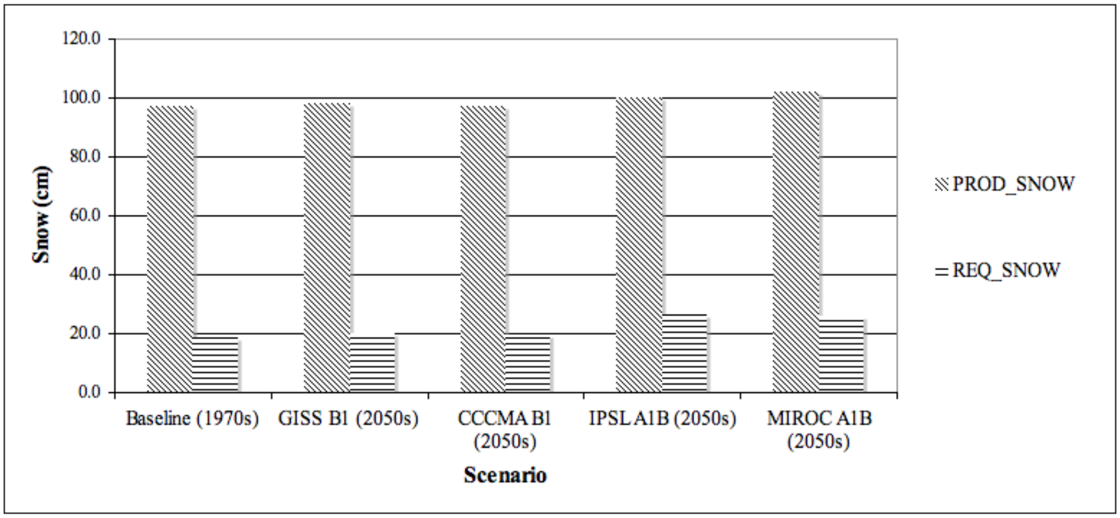
Losses, when assessed by season segment, follow a similar trend from the minimum elevation as all losses are accounted for during the low season (Figure 4.19). In the baseline scenario, the early season was modeled as having 44 days. Reductions during this segment are; 1 day (GISS B1), 3 days (CCCMA B1), 8 days (IPSL A1B) and 9 days (MIROC A1B). There are no losses to any other season segment modeled at this altitude. In the future, resorts will be required to begin operations later in the year requiring them to intensify operations and visitation during other segments to maintain profits. However, an encouraging finding is that under all scenarios skiable days during the high season are maintained and 100% of the years are likely to retain a fully operable Christmas/New Years segment during the 2050s. Again, these findings are promising as they infer that the bulk of revenue generating days within a typical season will be preserved regardless of future temperature increase and precipitation variation. This prediction was continued from the minimum elevation.

Figure 4.19: Copper Mountain Mean Altitude Season Segment Length



When examining artificial snow production and requirements at this altitude, projections are similar to the minimum altitude. During the 1961-1990 period, 97 cm was produced to establish the critical threshold. This is maintained in the GISS B1 scenario with no change registered, and increases to 98 cm (CCCMA B1), 100 cm (IPSL A1B) and 102 cm (MIROC A1B) (Figure 4.20). Under all scenarios there is likely to be an increase in REQ_SNOW, 19 cm of artificial snow was required during the 1970s to establish and maintain operations from December 15 - April 15. This value increases to 20 cm (GISS B1, CCCMA B1) in each of the 'least change' scenarios and further increases to 26 cm (IPSL A1B, MIROC A1B) in each of the 'most change' scenarios (Figure 4.20). Therefore, potential production throughout the season under technological constraints will continue to exceed projected requirements, allowing snowmaking to remain as an adaptation strategy in the 2050s.

Figure 4.20: Copper Mountain Mean Altitude Snowmaking

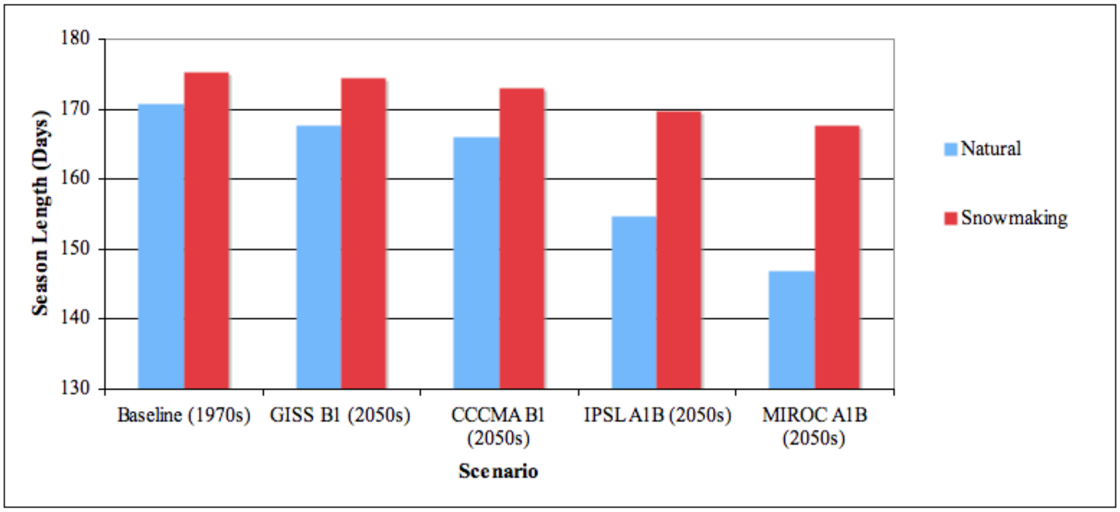


Maximum Altitude (3800m)

As expected, SkiSim 2 modeled the most favourable outcomes for Copper Mountain at its maximum elevation. This reasserts the importance of elevation on ski season length. An interesting deviation from the California case study for Copper was the influence of snowmaking on season length and the improvements in the outlook under a climatically changed future. The 1970s baseline natural season length was modeled at 171 skiable days and was reduced under all future scenarios. The most significant impacts, when snowmaking is not included, are forecast to occur under the MIROC A1B 2050s climate scenario and are followed by impacts under the IPSL A1B 2050s scenario. Respectively, these scenarios will result in reductions of 24 skiable days and 16 skiable days.

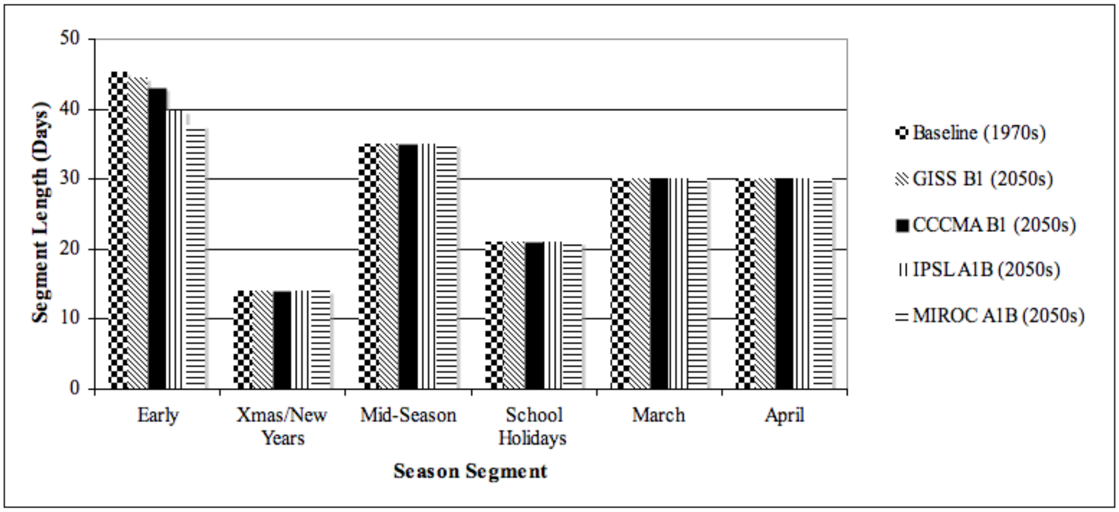
When inclusive of snowmaking, the 1970s ski season length was modeled at 175 days, an increase of only 4 days over natural conditions. Reductions to season length when inclusive of snowmaking are less pronounced than reductions under natural conditions alone. Under GISS B1 scenario conditions, season length will be reduced by 1 day with snowmaking compared to 3 days without, while under CCCMA B1 scenario conditions, season length will be reduced by 2 days with snowmaking compared to 5 days without (Figure 4.21). Under the 'most change' scenarios snowmaking has a more profound impact on maintaining season length. SkiSim 2 modeled reductions at 6 skiable days (IPSL A1B) and 7 skiable days (MIROC A1B) with snowmaking, these compare to the aforementioned reductions under natural conditions of 16 and 24 days respectively (Figure 4.21).

Figure 4.21: Copper Mountain Maximum Altitude Ski Season Length



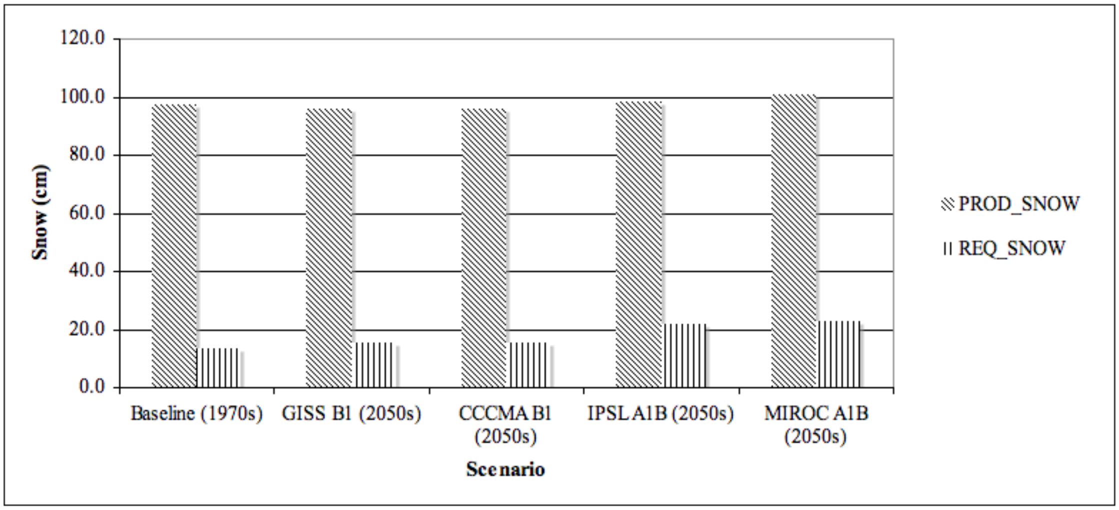
The timing of reductions throughout the season follows trends from the minimum and mean altitude, with all reductions occurring during the early season. Figure 4.22 provides a breakdown of skiable days throughout the season segments in the 2050s for Copper Mountain's maximum altitude. The baseline scenario was modeled as having 45 early season skiable days, this segment is reduced to 43 days (CCCMA B1) and 44 days (GISS B1) in the 'least change' scenarios. Reductions modeled for the 'most change' scenarios are slightly worse with the early season registering 40 skiable days (IPSL A1B) and 38 skiable days (MIROC A1B). Apart from the early season no other segment is predicted to have any reduction in skiable days. Two additional trends continued from the lower altitudes are that the high season is maintained at 100 skiable days under all future scenarios. Also, 100% of all years in the 2050s are projected to be able to maintain operations during the Christmas/New Years segment, an important forecast for revenues.

Figure 4.22: Copper Mountain Maximum Altitude Season Segment Length



The amount of artificial snow produced in PROD_SNOW at this elevation in the baseline scenario is 97 cm. Reductions of 2% are projected in each of the 'least change' scenarios, resulting in 96 cm (GISS B1, CCCMA B1) of artificial snow production needed in establishing the critical threshold. PROD_SNOW is likely to increase by 1% in the IPSL A1B (98 cm) scenario and by 4% in the MIROC A1B (101 cm) scenario (Figure 4.23). Meanwhile, 13 cm of artificial snow is required in the baseline scenario to offset natural snowfall in providing a ski product between December 15 and April 15. REQ_SNOW increases to 15 cm (CCCMA B1), 16 cm (GISS B1), 22 cm (IPSL A1B) and 23 cm (MIROC A1B). Under all future scenarios PROD_SNOW exceeds REQ_SNOW, suggesting that a minimum operational snow base of 30 cm can be sustained between December 15 and April 15, further suggesting that snowmaking will be a suitable adaptation to climate change (Figure 4.23).

Figure 4.23: Copper Mountain Maximum Altitude Snowmaking



Copper Mountain Overview

In evaluating the Copper Mountain ski area what becomes apparent is the influence of both snowmaking and elevation on sustaining skiable days. The impact of elevation is displayed through Figure 4.24. Baseline season length at the highest altitude is 23 days (+15%) without snowmaking, and 4 days (+2%) with snowmaking, longer than the lowest altitude. When averaged across the four future climate change scenarios, ski season length is 25 days (+18%) without snowmaking, and 7 days (+4%) with snowmaking, longer at the highest altitude compared to the lowest.

An interesting finding for this site is the direct correlation between snowmaking and elevation on extending season length. The efficacy of snowmaking in extending season length is also the reason why differences in ski season length between the lowest and highest altitudes, with snowmaking included, is so small. In the baseline scenario, natural season length was modeled at 148 days without snowmaking, increasing to 171 days with snowmaking. At the maximum altitude, exclusive of snowmaking, season length was also modeled at 171 days, increasing only to 175 days with snowmaking. This infers that with snowmaking employed, base operations are able to sustain as long a season as the summit altitude. If exercised, this strategy could significantly extend annual operations, reduce discrepancies in season opening dates between altitudes, and thus increase earnings at Copper Mountain. Figure 4.25 exhibits the improvements to lost skiable days during the low season with increasing elevation. Copper Mountain is likely to sustain the entire 100-day high season in all future scenarios at all elevations examined. The decrease in skiable days during the low season with increasing elevation further solidifies the likelihood of ski operations remaining plausible into the 2050s at this site.

When considering future climate change conditions, snowmaking is effective in preserving season length. At the lowest altitude averaged across the four scenarios, ski season length reductions with snowmaking are 50% of reductions without snowmaking. While at the highest altitude, season length reductions (averaged across the four scenarios) with snowmaking are approximately one-third (34%) of those projected without it. Furthermore, because PROD_SNOW exceeds REQ_SNOW at all elevations the use of snowmaking will remain a viable adaptation option. The decreased reliance on snowmaking, in sustaining key revenue generating periods, with increasing elevation is portrayed in Figure 4.26. This reasserts the importance of elevation on maintaining ski operations under a climatically warmer future.

Figure 4.24: Copper Mountain Ski Season Length (With Snowmaking)

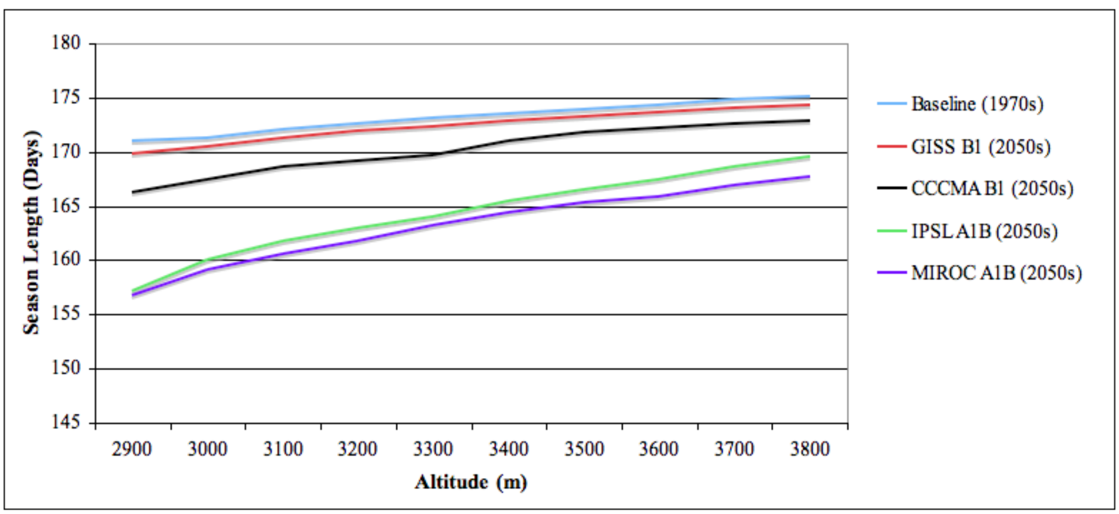


Figure 4.25: Copper Mountain Low Season Length (Nov. 1-Dec. 21, Apr. 1-Apr. 30)

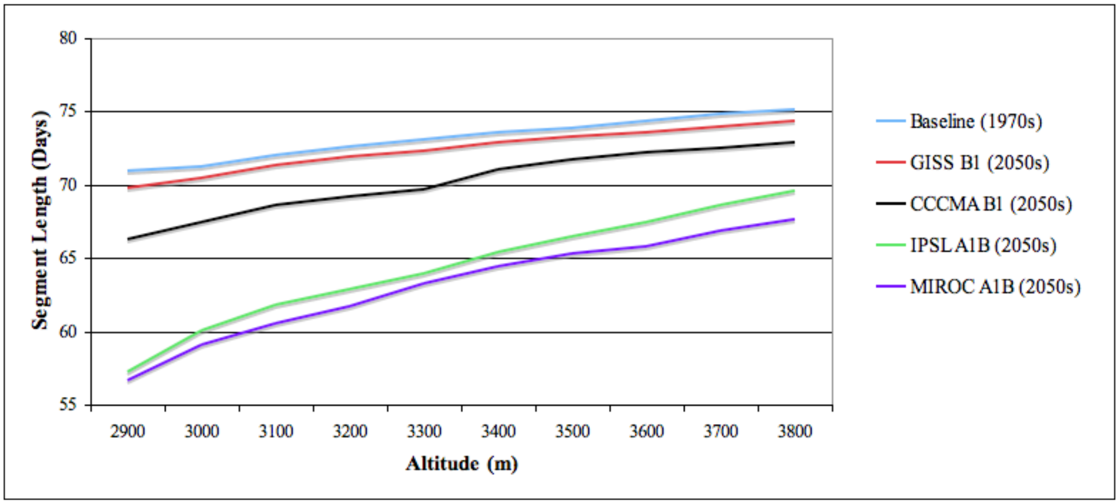
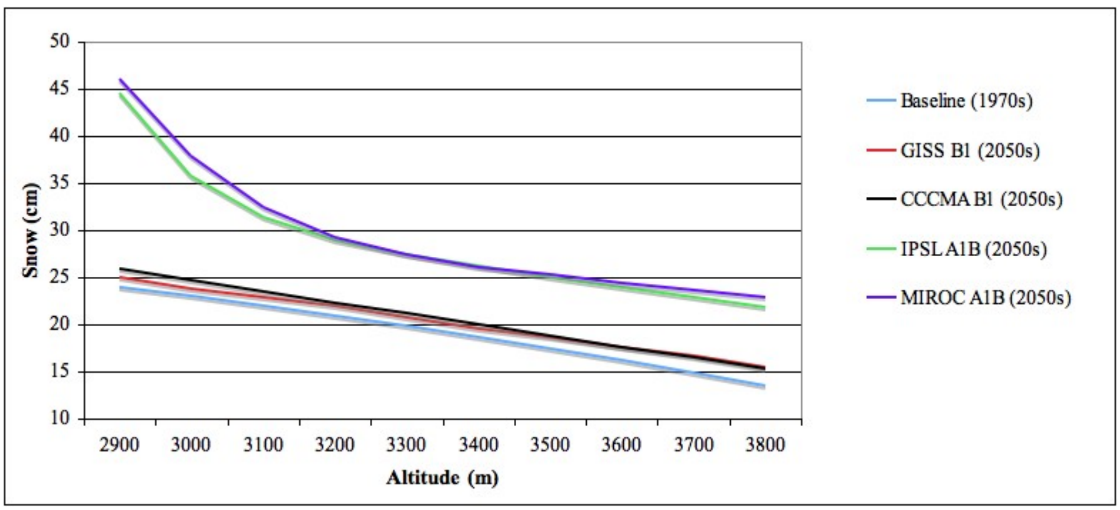


Figure 4.26: Copper Mountain Required Snowmaking



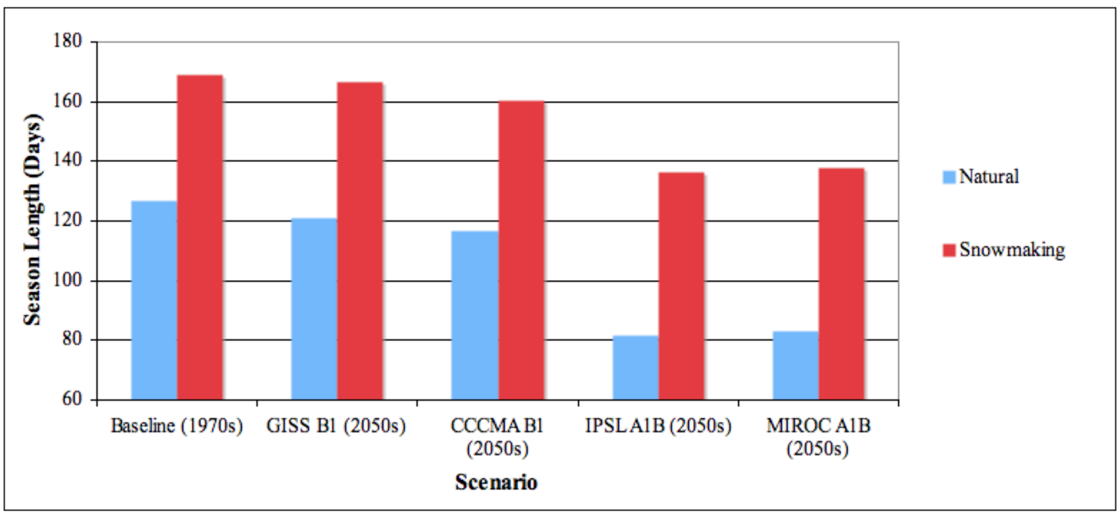
Vail (Colorado)

Minimum Altitude (2500m)

Vail's projected impacts from climate change at this altitude are moderate under the four future change scenarios. SkiSim 2 modeled Vail's baseline season length, with natural snowpack, at 127 skiable days. Natural season length is reduced under all future scenarios, the 2050s GISS B1 projections are the most favourable at 121 days, followed by an 117 day (CCCMA B1) season, an 83 day (MIROC A1B) season and 81 day (IPSL A1B) season. These latter projections jeopardize future ski operations, as season length does not fulfill the 100-day rule.

When snowmaking is incorporated in Vail ski operations modeling, the baseline season length is 169 days. This is an increase of 33% (42 days) over natural conditions alone. Reductions to skiable days due to warmer climates are also more limited when snowmaking is included. The GISS B1 2050s scenario exemplifies this best, as the reduction to skiable days is 33% of that projected for natural conditions when inclusive of snowmaking. The A1B scenarios also have drastic reductions to lost skiable days when snowmaking is incorporated in projections; the number of lost skiable days is reduced by 70% (MIROC A1B) and 71% (IPSL A1B) in relation to natural season length reductions (Figure 4.27). Notably, with snowmaking included, season length under these 'most change' scenarios still exceeds the 100-day rule, an encouraging projection given this is the lowest altitude for operations at Vail.

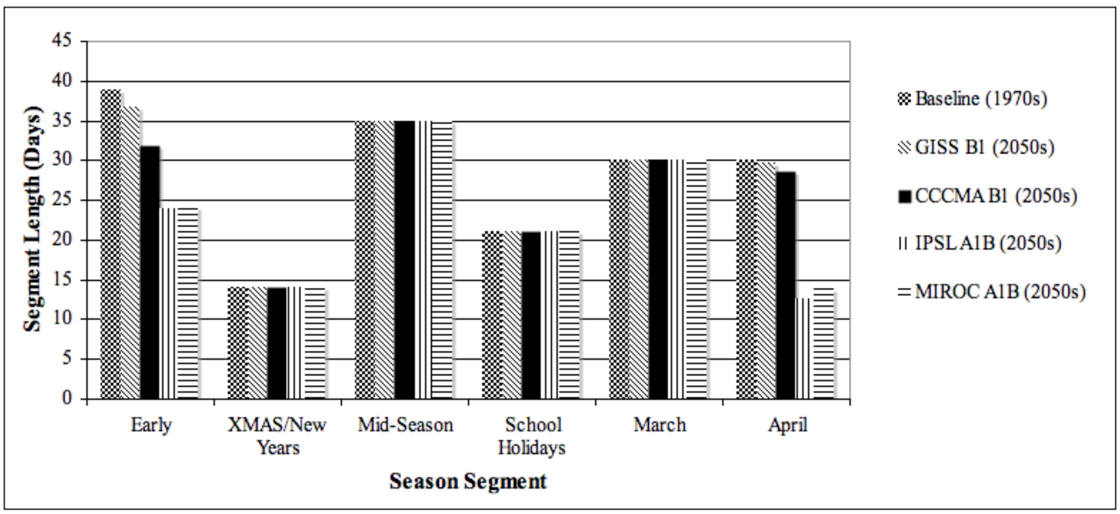
Figure 4.27: Vail Minimum Altitude Ski Season Length



Another promising projection for Vail is the preservation of all 100 skiable days throughout the high season. This implies that ski operations will remain possible from December 21 through March 30, sustaining the bulk of ski areas' revenue generating days. In addition to this, the findings suggest that there will be limited inter-season variability as 100% of years throughout the 2050s are likely to remain operable during the Christmas/New Years period. Individually these predictions are promising, together they indicate a high level of resilience to a warmer climate.

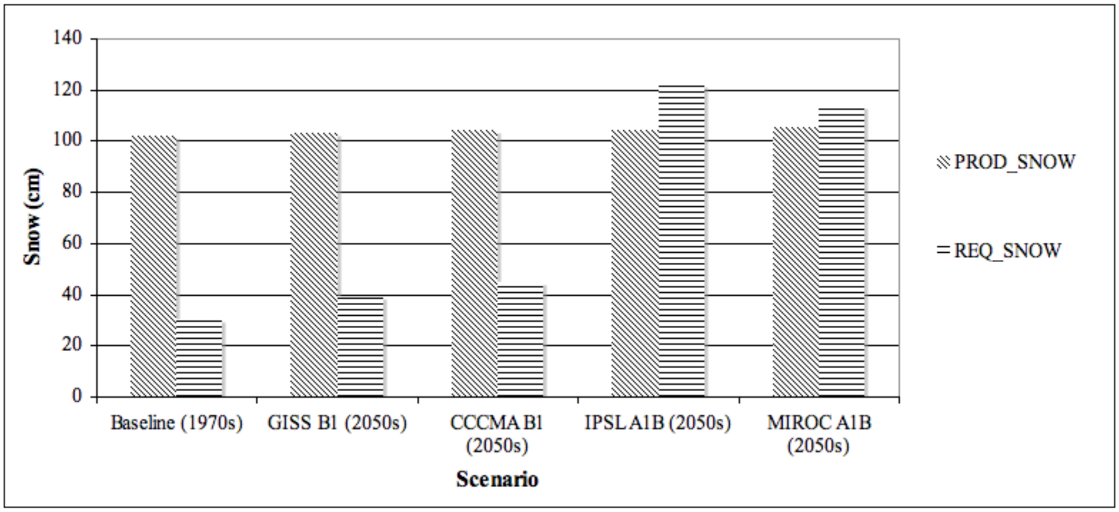
Reductions to skiable days for Vail are predicted to occur during the early and April segments (Figure 4.28). Under the 'least change' scenarios losses are largely predicted to occur during the early season with only minor reductions to April's operations. In the baseline scenario, SkiSim 2 modeled these individual segments at 39 days (early season) and 30 days (April). The early season is reduced to 37 skiable days (GISS B1), 32 skiable days (CCCMA B1) and 24 skiable days (MIROC, IPSL) in each of the A1B scenarios (Figure 4.28). The April segment is sustained into the 2050s under GISS B1 conditions at 30 days, being reduced to 29 days (CCCMA B1), 14 days (MIROC A1B) and 13 days (IPSL A1B) (Figure 4.28). The implication is that Vail will no longer be able to open on its historical date, November 15, forcing visitation to be intensified during other season segments. This adaptation approach will be more limited in successfully reducing the vulnerability of ski operations under the two 'most change' scenarios, as these also have significant reductions at the end of the season.

Figure 4.28: Vail Minimum Altitude Season Segment Length



During the baseline scenario, 102 cm of artificial snow was modeled as the amount necessary to establish the critical snowpack threshold to maintain the minimum operable snow base until April 15. Fortunately at this elevation climate conditions will remain sufficient to increase artificial snow production. PROD_SNOW increases under all future scenarios; 103 cm (GISS B1), 104 cm (CCCMA B1, IPSL A1B), and 105 cm (MIROC A1B) will be required to be produced to sustain ski operations throughout the entire season (Figure 4.29). Artificial snow requirements (REQ_SNOW) to maintain operations during the key revenue generating days also increased under all future scenarios. While REQ_SNOW was modeled at 30 cm for the baseline period, it increased to 39 cm (GISS B1) and 45 cm (CCMA B1) under the ‘least change’ scenarios, further increasing to 114 cm (MIROC A1B) and 122 cm (IPSL A1B) under the two ‘most change’ scenarios (Figure 4.29). Only in the ‘most change’ scenarios is a deficit likely to occur between artificial snow requirements and productions throughout the season.

Figure 4.29: Vail Minimum Altitude Snowmaking



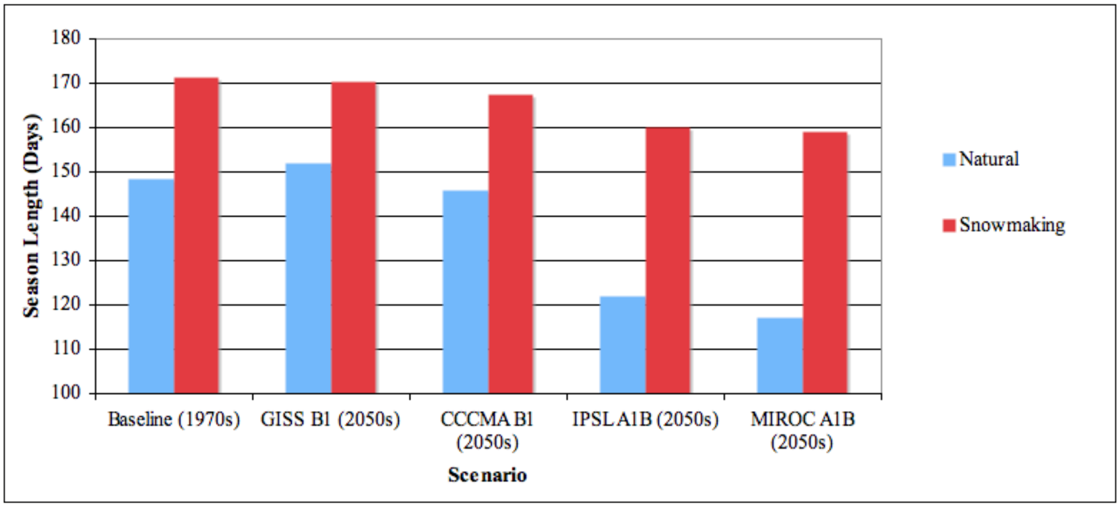
Mean Altitude (3000m)

The increase in altitude of 500m above the minimum elevation had a direct impact on the outlook of future ski operations at Vail during the 2050s; significantly much less impacts were projected. Season length in the baseline scenario, without snowmaking, was modeled at 148 skiable days, an increase of 21 days above the minimum altitude. In consideration of the future climate change scenarios, season length is reduced to 146 days (CCCMA B1), 122 days (IPSL A1B) and 117 days (MIROC A1B) (Figure 4.30).

SkiSim 2 modeled season length at 152 days in the GISS B1 2050s scenario, an increase of 2% over baseline season length. Similar to select GISS B1 projections for Copper Mountain, this increase is projected because of current average temperature and precipitation, combined with minimal temperature increase (Nov-March) and increased precipitation in November in the 2050s. This results in more natural snowfall in the early season, thus increasing the number of skiable days. The season length reported is the average for the 30-year period (2050s), the degree of warming projected in this scenario is not significant enough to impact ski season length past current climate variability. Again however, a difference of this magnitude (+2%) is deemed no change.

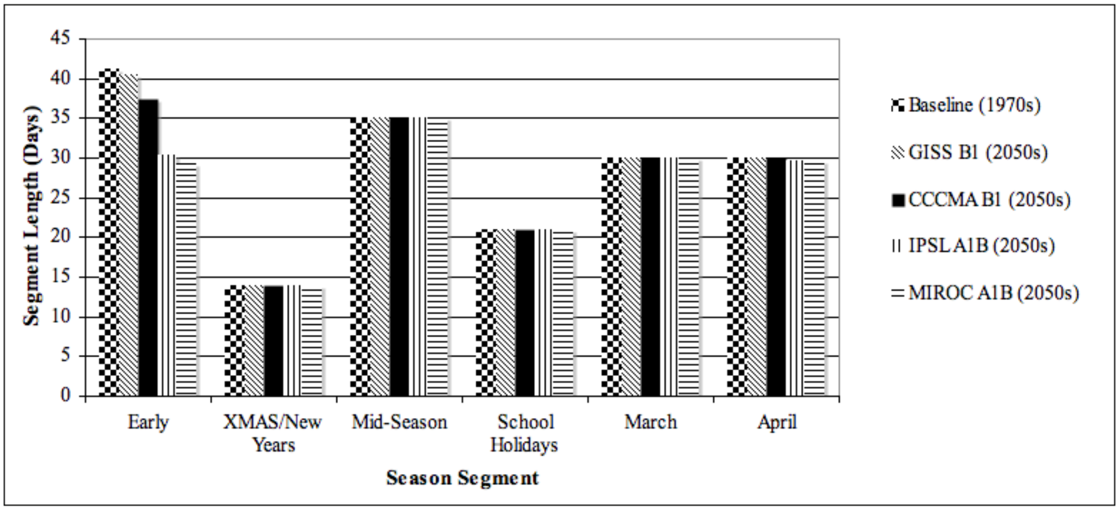
When inclusive of snowmaking, season length for the 1970s was modeled at 171 skiable days, an increase of 16% over natural conditions. This figure is reduced however under all future climate change scenarios. GISS B1 predictions are most favourable with a one-day reduction in season length by the 2050s. It is followed by skiable days being reduced to 167 days (CCCMA B1), 160 days (IPSL A1B) and 159 days (MIROC A1B) (Figure 4.30).

Figure 4.30: Vail Mean Altitude Ski Season Length



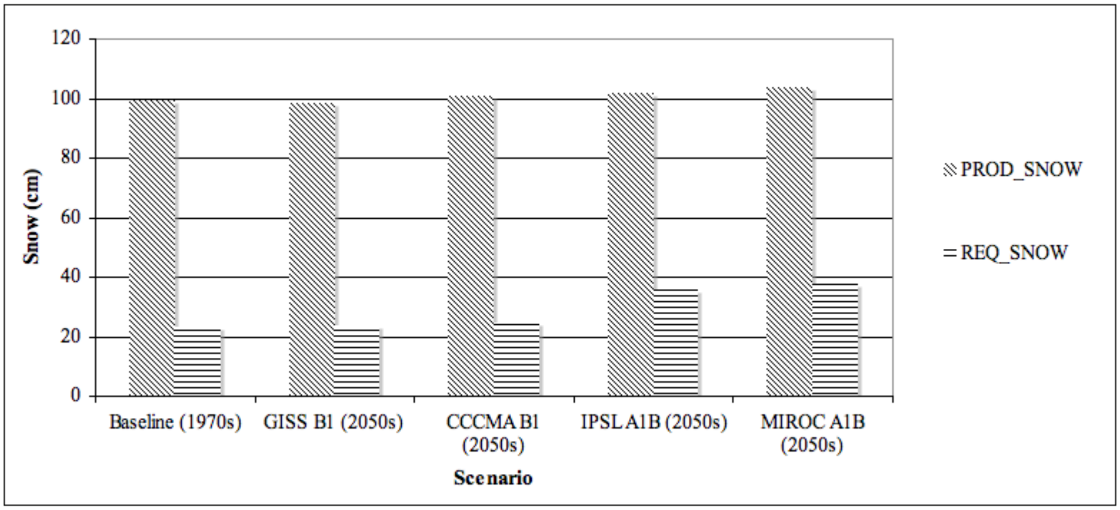
Reductions in skiable days at Vail ski area are largely projected for the early season, under all 2050s scenarios. SkiSim 2 modeled the baseline scenario as having an early season of 41 skiable days and an April segment at 30 skiable days. Under the ‘least change’ 2050s scenarios, early season losses are 1 day in the GISS B1 scenario and increase to 4 days in the CCCMA B1 scenario. More severe reductions are expected under the ‘most change’ scenarios with losses of 11 days (IPSL A1B) and 12 days (MIROC A1B) during the early season. SkiSim 2 modeled minimal reductions to April, which were only modeled under the IPSL A1B and MIROC A1B scenarios. These decreases amount to less than 1 day for each scenario and thus considered negligible. Continued from the minimum altitude, Vail’s entire high season is preserved under the breadth of future climate scenarios. Figure 4.31 displays reductions in season segment’s length for Vail’s mean altitude. Together the individual high season segments will uphold the 100-day rule. This is strengthened by the prediction that 100% of years during the 2050s will remain open during the vital Christmas/New Years segment. Due to the combination of factors listed above, ski operations at this altitude will remain plausible through the 2050s.

Figure 4.31: Vail Mean Altitude Season Segment Length



At this elevation, SkiSim 2 modeled the potential for 99 cm of artificial snow to be produced in the baseline scenario to establish the critical snow depth threshold in maintaining the 30 cm minimum until April 15. PROD_SNOW drops to 98 cm in the GISS B1 scenario but increases in the rest to 101 cm (CCCMA B1, IPSL A1B), and 103 cm (MIROC A1B) (Figure 4.32). The required amount of artificial snow, without considering technological constraints, to maintain the high season at this elevation is considerably reduced relative to the minimum elevation (Figure 4.32). In the 1970s period, SkiSim 2 found that 23 cm of snow was required to maintain the minimum snow depth between December 15 and April 15 only. REQ_SNOW increases by the 2050s in each climate scenario, to 24 cm in the GISS B1 scenario, 25 cm in the CCCMA B1 scenario, 36 cm in the IPSL A1B scenario and 38 cm in the MIROC A1B scenario. Fortunately, at this elevation projected snowmaking requirements are exceeded by the potential for necessary production throughout the season.

Figure 4.32: Vail Mean Altitude Snowmaking



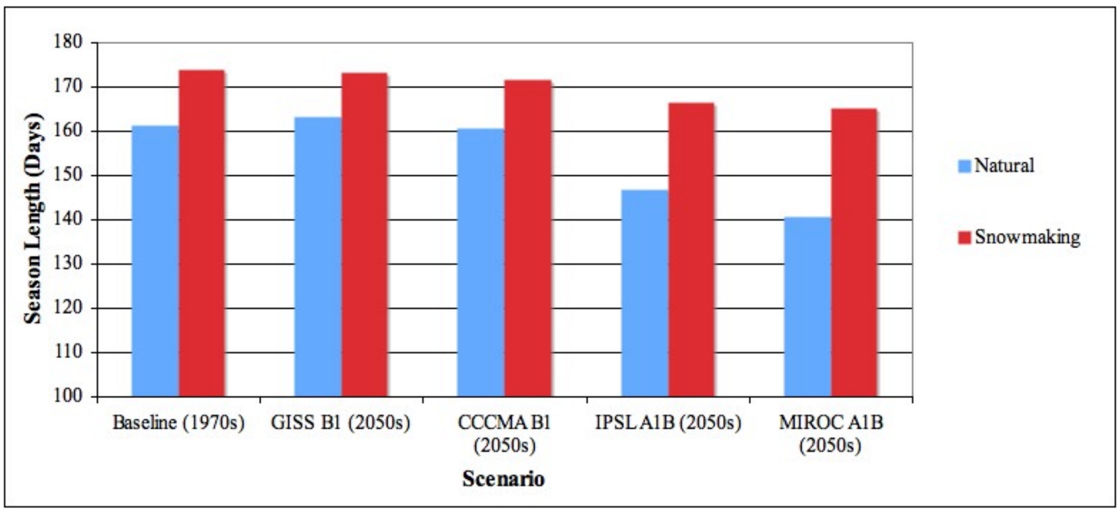
Maximum Altitude (3500m)

Continuing the improvement in projections for the mean altitude over the minimum altitude, ski operations are most likely to be preserved at this elevation under climatically warmer futures. This is the same for scenarios both inclusive and exclusive of snowmaking. For the 1970s, natural season length was modeled at 161 skiable days. Under the two 'most change' scenarios SkiSim 2 modeled a 9% and 13% reduction to season length, resulting in 147 skiable days (IPSL A1B) and 141 skiable days (MIROC A1B), without snowmaking. SkiSim 2 modeled a 2 day increase in skiable days in the GISS B1 scenario, again considered a no change scenario due to projections being more dependent on inter-seasonal climate variability, averaged over the 30-year period (2050s), than future climate change. No differences are also projected under the CCCMA B1 scenario (Figure 4.33).

Despite these findings for natural ski season length in the B1 scenarios, there are reductions to ski season length projected in each of these scenarios when inclusive of snowmaking. However, its use will serve to provide a longer baseline ski season length from which reductions occur. Baseline season length (174 skiable days) when snowmaking is included increases by 8% over natural snowpack alone, 2050s B1 scenarios ski season length when snowmaking is included is projected to be 172 skiable days (CCCMA B1) and 173 skiable days (GISS B1). Again, despite reductions, the ski season, when inclusive of snowmaking, is 11 and 10 days longer than under natural snow conditions. However, since these reductions are so small (-1% CCCMA B1, <1% GISS B1) they are deemed no change (Figure 4.33).

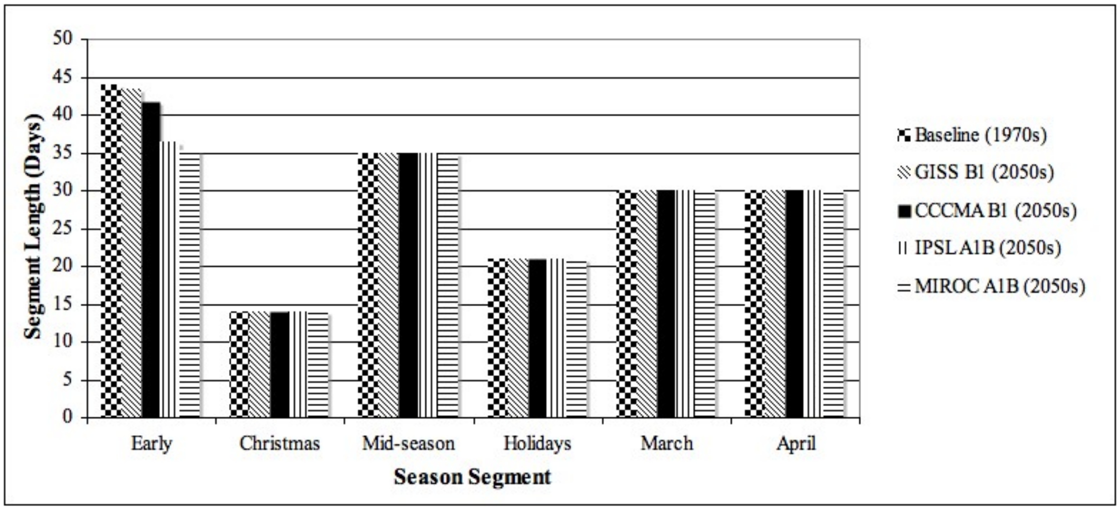
As displayed through most other projections, the efficacy of snowmaking in mitigating adverse season length impacts from climate change is most distinct under the 'most change' scenarios. At this elevation, by the 2050s, season length with snowmaking will be reduced to 166 days (IPSL A1B) and 165 days (MIROC A1B) (Figure 4.33). These amount to reductions of 7 days and 9 days, respectively, and compare to 14 and 20 days lost under the same climate scenarios when snowmaking is not included.

Figure 4.33: Vail Maximum Altitude Ski Season Length



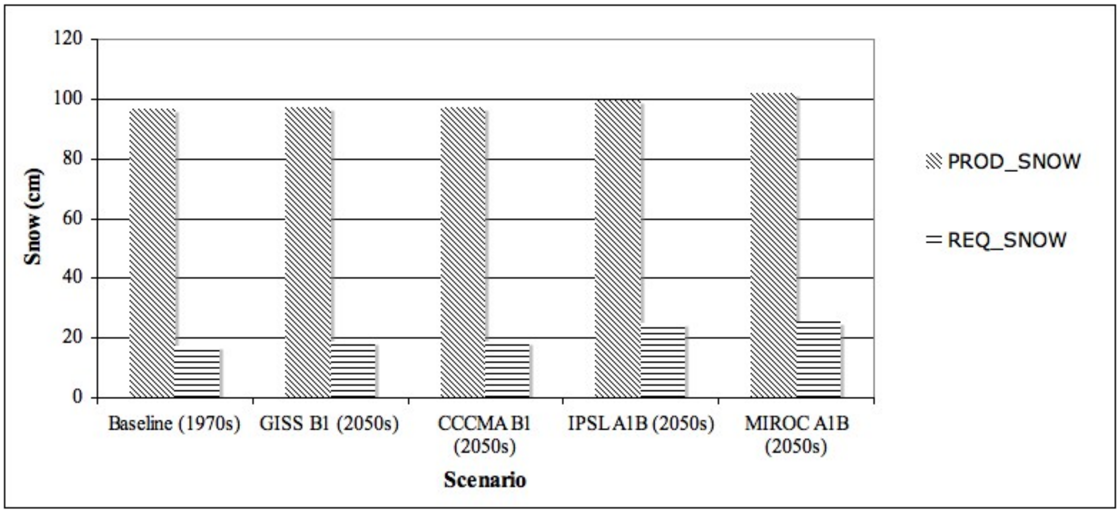
The early season is the only segment with any reduction to skiable days by the 2050s at Vail's maximum altitude. The early season in the 1970s was modeled at 44 skiable days. Under future climate change scenarios this is reduced to 43 days (GISS B1), 42 days (CCCMA B1), 36 days (IPSL A1B) and 35 days (MIROC A1B). Unlike the lower two altitudes examined, these reductions will still allow Vail to maintain its current typical opening date of November 15 under all future scenarios. In addition to preserving the majority of all season segments, the Christmas/New Years period is likely to remain operable in 100% of the years throughout the 2050s. Figure 4.34 outlines season segment length at this altitude when inclusive of snowmaking. It is unlikely that ski operations will be drastically impacted by climate change when snowmaking is implemented. The relative continuation, to other altitudes, of season length, together with favourable inter-season reliability, signifies a high level of resilience to climate change for ski operations at Vail's maximum altitude.

Figure 4.34: Vail Maximum Altitude Season Segment Length



Vail's maximum altitude requires the least dependence on artificial snow during both the 1970s and 2050s. Figure 4.35 displays PROD_SNOW and REQ_SNOW projections for the baseline and future climate change scenarios. In the baseline scenario, a total of 97 cm would be produced under the defined capacity to reach the critical threshold in maintaining 30 cm minimum snow depth to April 15. This is maintained in both the GISS B1 and CCCMA B1 scenarios, with increases projected under the IPSL A1B (99 cm) and MIROC A1B (102 cm) scenarios (Figure 4.35). Artificial snow requirements, between December 15 and April 15, are the lowest for all of Vail ski area at this elevation. In the baseline scenario, 17 cm of snow would be required to maintain the minimum snow depth. When projected to the 2050s, 19 cm of snow would be required to maintain this same depth under the 'least change' scenarios while 25 cm would be required under the 'most change' scenarios (Figure 4.35).

Figure 4.35: Vail Maximum Altitude Snowmaking



Vail Overview

Projections of future ski operations at Vail ski area are consistent with outcomes for Squaw Valley and Copper Mountain. First, the importance of elevation on viable ski operations is apparent for this site. Displayed in Figure 4.36, there is an increase in skiable days from the minimum to maximum altitude in all scenarios and timeframes examined. At the highest altitude, ski season length is 27% (without snowmaking) and 3% (with snowmaking) longer than the lowest altitude. When averaged across the four climate change scenarios, ski season length at the maximum altitude is 52% (without snowmaking) and 13% (with snowmaking) longer than the minimum altitude. This is supported through projections of the low season, which also has substantial increases in length with increasing elevation (Figure 4.37)

A second encouraging finding for Vail is its ability to sustain the total duration of the high season under all future climate change scenarios at all elevations. This, along with promising projections of inter-season Christmas/New Years, suggests Vail's revenues be sustained into the 2050s. However, snowmaking costs are likely to increase operating expenses, which could negatively impact the ski area's financial bottom line.

A third finding continued from Squaw Valley and Copper Mountain is the importance of snowmaking on extending and preserving ski season length. Though its impact becomes more negligible with increasing elevation, its efficacy is undeniable. The relationship between elevation and required snowmaking is displayed in Figure 4.38. At the base altitude when snowmaking is included, season lengths are increased under all scenarios at both timeframes. Interestingly, with snowmaking included at the lowest elevation, baseline season length increases to 169 skiable days, which is 8 days longer than season length under natural conditions and only 5 days less than season length with snowmaking included at the maximum altitude. Similar to Copper Mountain, this suggests that if snowmaking were to be employed to a large extent, operators would be able to reduce discrepancies in opening dates, allowing a greater portion of the hill to commence operations sooner. An auxiliary result would be a decreased reliance on natural snowfall to provide a consistent ski product during key season segments as a sufficient snowpack could be established to ensure operations. Further supporting its use, when considering future change scenarios, snowmaking inclusive losses are reduced by up to 66% of those projected when exclusive of snowmaking. The outcome of these findings, applicable also to Copper Mountain, is that a ski product is likely to be better maintained at Vail than other ski areas or regions.

Figure 4.36: Vail Ski Season Length (With Snowmaking)

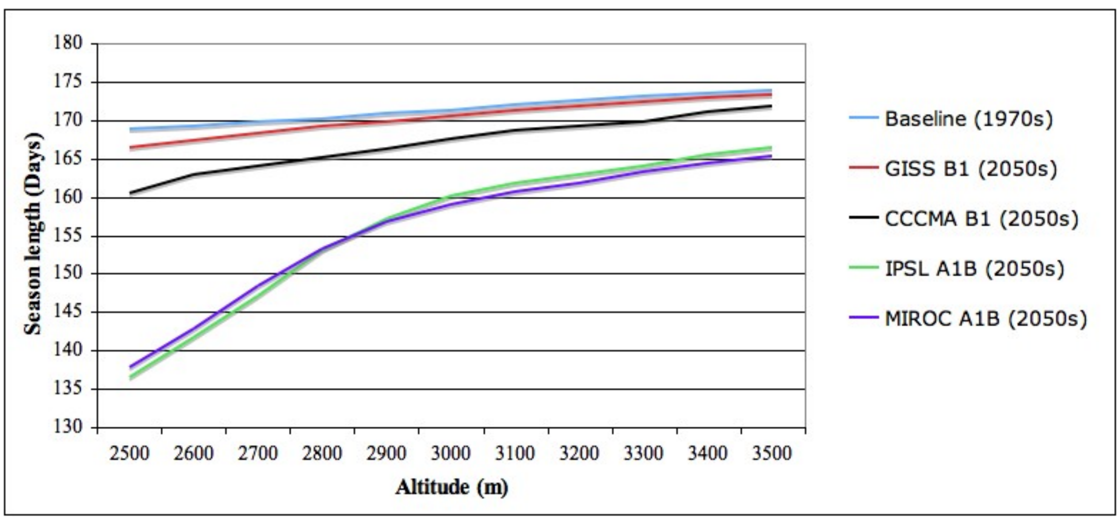


Figure 4.37: Vail Low Season Length (Nov. 1 – Dec 21, Apr. 1 – Apr. 30)

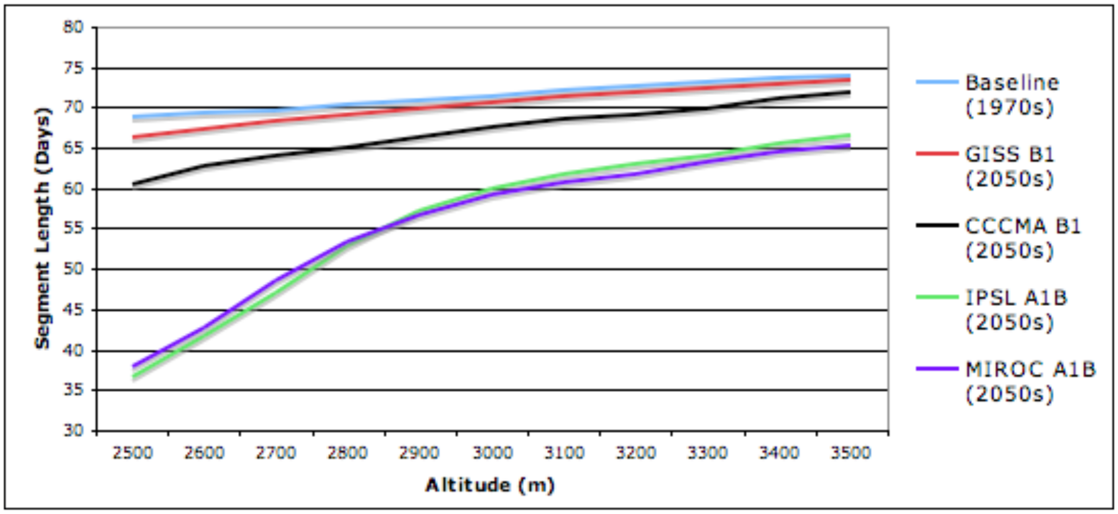
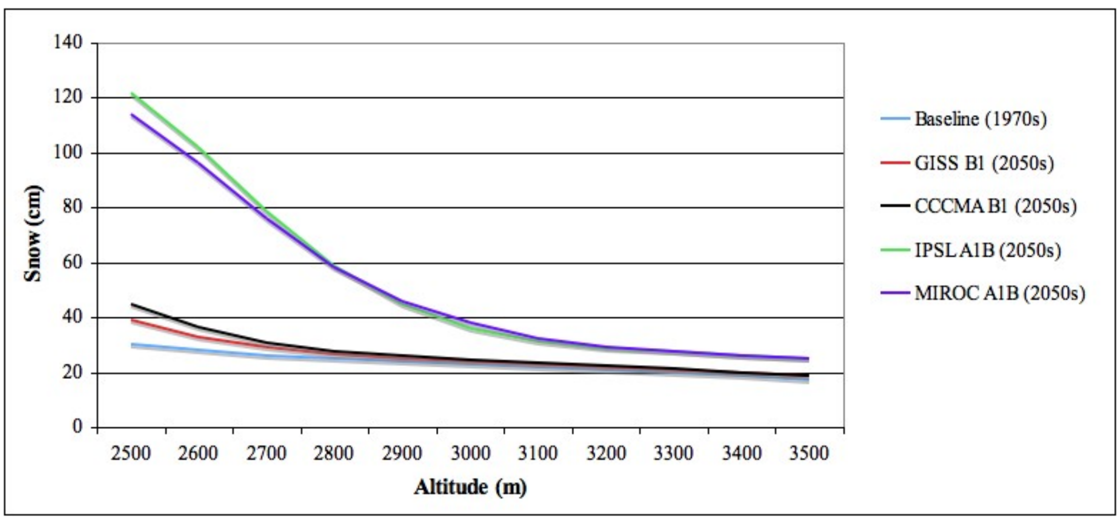


Figure 4.38: Vail Required Snowmaking



5. Discussion

Introduction

This chapter discusses the probable climate change impacts on ski operations in the study areas of Colorado and California, including: season length, individual season segments and snowmaking. The primary consideration of this thesis' findings was to reassess previous claims regarding climate change and the ski industry in Colorado and California. Following this reassessment, the adaptation potential of snowmaking is discussed. It is argued that economic and environmental constraints to snowmaking may limit its application beyond projected climate change. Lastly, suggestions for ski areas to reduce their climate change vulnerability are provided.

Comparative Vulnerability of Squaw Valley vs. Vail vs. Copper Mountain

Climate change will impact ski operations to varying degrees both between the destinations examined and within ski area's altitudinal distribution. It is important to state that, even in the baseline scenario, Colorado is better suited to providing longer ski season lengths due to the higher average elevation of ski areas and colder average winter temperatures. Altitude also serves to differentiate impacts within ski areas, as higher altitude operations are more resilient to projected climate.

Table 5.1: Summary of Projected 2050s Ski Season Length

Ski Area	Snow Condition	Altitude								
		Low			Mean			High		
		1961-1990 Ski Season Length (Days)	2050s Best Case (%)	2050s Worst Case (%)	1961-1990 Ski Season Length (Days)	2050s Best Case (%)	2050s Worst Case (%)	1961-1990 Ski Season Length (Days)	2050s Best Case (%)	2050s Worst Case (%)
Squaw Valley	Natural	98	-31.2	-85.5	152	-6.5	-42.9	165	-1.9	-6.4
	Snowmaking	137	-8.1	-71.8	154	-2.4	-15.6	168	-1.8	-8.3
Copper Mountain	Natural	148	2.4	-21.1	158	1.7	-13.3	171	-1.8	-13.9
	Snowmaking	171	-0.5	-7.1	174	-0.4	-5.2	175	-0.5	-4.3
Vail	Natural	127	-4.4	-34.6	148	2.4	-21.1	161	1.3	-12.7
	Snowmaking	169	-1.4	-18.3	171	-0.5	-7.1	174	-0.3	-5.0

Table 5.2: Summary of Projected 2050s Artificial Snow Production

Ski Area	Snowmaking Output	Altitude								
		Low			Mean			High		
		1961-1990 Snow Amount (cm)	2050s Best Case (%)	2050s Worst Case (%)	1961-1990 Snow Amount (cm)	2050s Best Case (%)	2050s Worst Case (%)	1961-1990 Snow Amount (cm)	2050s Best Case (%)	2050s Worst Case (%)
Squaw Valley	REQ_SNOW	50	56.0	381.0	16	22.0	374.0	5	70.0	280.0
Copper Mountain	REQ_SNOW	23.0	4	65	18.6	5	40	13.4	15	70
Vail	REQ_SNOW	30.0	30	380	23.0	4	65	17.4	7	45

Under the 2050s climate change scenarios, Colorado continues to be better posed to sustain baseline ski season length. Compared to Squaw Valley, Copper Mountain's average season length under the four future scenarios at the lowest elevation is 238% (natural) and 109% (snowmaking included) longer, while Vail's is 153% (natural) and 91% (snowmaking included) longer. In comparing the average (across the four future scenarios) loss to ski season length, without snowmaking, Squaw Valley's lowest altitude ski season is reduced by 60%, which compares to 21% at Vail and 10% at Copper Mountain. In projections inclusive of snowmaking, ski season length is reduced by 43% (Squaw Valley), 11% (Vail) and 4% (Copper Mountain) at the lowest altitude. At the mean altitude, Squaw Valley's average season length is reduced by 23% (natural) and 9% (snowmaking included), while for Vail it is reduced by 10% (natural) and 4% (snowmaking included), and at Copper Mountain it is reduced by 5% (natural) and 3% (snowmaking included). The difference in projected ski season length reductions becomes negligible between the three ski areas at the highest altitudes.

Projections of snowmaking under the assessed climate change scenarios also position Colorado's ski areas in a more favourable position than California's. This is seen in both outputs of snowmaking in SkiSim 2. The capacity to produce snow (PROD_SNOW), is reduced in select scenarios at all three ski areas. What becomes alarming for Squaw Valley is that this capacity is reduced by up to 26%, while for both Colorado ski areas it is reduced by only 1% - effectively no change for Colorado ski areas. For Squaw Valley's lowest altitude, the critical temperature threshold for artificial snow production is surpassed with more pronounced climate change, resulting in additional losses to skiable days throughout the revenue-important high season. This threshold is not passed at either of the Colorado sites, better positioning ski areas to supply a consistent ski product into the 2050s.

The requirement for artificial snow (REQ_SNOW) is significantly larger for Squaw Valley than either Vail or Copper Mountain. While requirements are analogous between Squaw Valley's and Vail's minimum altitudes, there is a distinct drop modeled in REQ_SNOW with increasing elevation at Vail not modeled for Squaw Valley. A comparison of Squaw Valley to Copper Mountain further illustrates differences in REQ_SNOW. Copper Mountain's lowest altitude, the most vulnerable location of the ski area, under the 'most change' IPSL A1B scenario, requires a 56% increase. While Squaw Valley's highest altitude, the least vulnerable location of the ski area, under 'least change' GISS B1 scenario, requires a 40% increase. These relatively similar projections occur despite a 1900 m difference in elevation.

Snowmaking becomes a significant challenge for Squaw Valley, and to lesser degree Vail but not Copper Mountain, as evidenced by projections where REQ_SNOW exceeds PROD_SNOW. At Squaw Valley's lowest altitude, the MIROC A1B scenario requires 191 cm of artificial snow, while only 67 cm will be able to be produced under current capacities. The IPSL A1B scenario at Vail's lowest altitude presents a similar dilemma, as 122 cm of snow is required to maintain the December 15 – April 15 period, while only 104 cm will be able to be produced.

The relationship between altitude and operations is evident at each site, as displayed in Figure 4.10, Figure 4.24 and Figure 4.36. At Squaw Valley, natural season length at the maximum altitude, averaged across the four future scenarios, is 299% longer than at the lowest altitude. At Vail and Copper Mountain, natural season length averaged across the four climate change scenarios is 52% (Vail) 18% (Copper Mountain) longer at the highest altitude relative to the lowest. This is further illustrated by the above statement that differences in reductions to season length, averaged across the four climate change scenarios, is negligible between the California and Colorado ski areas' highest altitude.

Reassessment of Previous Claims

Previous academic and media claims on the potential impacts of climate change on ski operations were found to not adequately account for potential adaptation strategies, and as a result, suggest much greater impacts from climate change.

California

Hayhoe et. al. (2004) constitutes the only known research to date on the impact of future climate change on the ski industry in California. While the findings from Hayhoe et al. (2004) are in line with some findings from this study, there are limitations in their methodology that must be considered. Hayhoe et. al. (2004) predict reductions to ski season length due to reduced snow pack as a result of potential climate change, with impacts most likely to arise during the early season.

When comparing the reductions to season length predicted in Hayhoe et. al. (2004) with this work, a key difference is the impact to ski operations at various altitudes. Hayhoe et. al. (2004) contend that by 2100, ski season length will be reduced by 49-103 days using the PCM model, while “under the HADCM3, similar delays occur by mid-century” for all elevations under 3000 masl (pp. 4, supporting material). These projected changes only resemble those at the lowest altitudes in this research, with and without snowmaking according to the climate change scenario.

When averaged across the four scenarios analyzed, at the lowest altitude (1900 masl), ski season length is reduced by 58 (natural conditions) and 59 (snowmaking) days in this work, in line with only the most conservative projections in Hayhoe et. al. (2004). The analogous reductions between projections inclusive and exclusive of snowmaking can be explained through a substantially longer baseline ski season when snowmaking is included, also due to sustained substantial reductions under the A1B scenarios. When snowmaking is included at the lowest altitude under the ‘least change’ scenarios (B1), season length reductions are 25% (CCCMA B1) and 77% (GISS B1) less than the most conservative projections in Hayhoe et. al. (2004).

At the mean altitude (2350 masl), this work projects much more favourable ski season length reductions, only those under natural conditions marginally resemble Hayhoe et. al.’s (2004) projections. In this work, when averaged across the four future scenarios, 35 days are projected to be lost under natural conditions, while only 14 days are lost when snowmaking is included. The snowmaking inclusive projections, averaged across the climate change scenarios analyzed, in this work are 71% less than Hayhoe et. al.'s (2004) most favourable projections.

At the maximum altitude (2800 masl), season length reductions with snowmaking are 81% (averaged across the four future scenarios) below the most favourable scenarios in Hayhoe et. al. (2004). Assuming snowmaking is fully implemented at the highest altitudes in the future, potential reductions to ski season length are much less in comparison between this study and Hayhoe et. al. (2004). These projections, inclusive of snowmaking, provide a more reasonable assessment of future impacts.

Hayhoe et. al.'s (2004) finding that season openings will be delayed is also questioned. The delays projected by Hayhoe et. al. (2004) are not modeled for even the lowest altitude with existing snowmaking accounted for by SkiSim 2, though delayed opening were projected in this study. Depending on the model used in assessing future SWE, Hayhoe et. al. (2004) found that seasons are likely to be delayed by 22 to 29 days by either 2050 or 2100; under the HADCM3 model by 2100 the minimum requirement for snow depth to provide a ski season is not met. At the minimum altitude in this study, where impacts are most severe, season openings are only delayed by 5 to 11 days by the 2050s. These figures are inclusive of snowmaking, therefore it is possible that without snowmaking more severe delays will occur, however, that does not reflect current operating realities.

Clearly, when a ski operations model that incorporates snowmaking is used to project potential impacts from a changing climate the findings are much more favourable. The work of Hayhoe et. al. (2004) does provides very important, and relevant, insight into future SWE in California, as their methodology is proven in assessing this variable. However, these insights project overly negative futures for ski operations, misrepresenting the outlook of this industry.

The 2020s and 2050s have been the timeframes of choice in previous vulnerability assessments since projections past these dates lose relevance for ski area managers and their decision-making (Scott et. al. 2006). Hayhoe et. al. (2004) do provide projections to the 2050s, however, impacts by 2100 are the focus of their research.

Modeling operations at the end of the century has minimal impact on the likelihood of such changes occurring, rather it simply renders projections irrelevant.

The authors lack context for the reductions projected as they only state that "the beginning of the snow season tends to fall during the last week of November, and it lasts until late June" (Hayhoe et. al. 2004, supporting material). They do not provide a quantified baseline season length from which projected reductions occur, nor do they provide a percentage reduction that would indicate the length of the remaining ski season. As an example, in their more severe projections, season length is reduced by 103 days, however, Hayhoe et. al. (2004) do not indicate how many days this was reduced nor the length of the season remaining. The reader is simply provided with a reduction, in potential skiable days, to season length. Furthermore, their statement that the ski season lasts from November to June is an inaccurate assessment of current average ski season length (skilaketahoe.com 2011). While according to the defined 'skiable day' thresholds, a ski season would be possible in select areas within California throughout this period, it is uncommon for the ski season to consistently last until June. As communicated in the previous chapters, current average ski season in the Lake Tahoe region lasts from the middle of November to the middle of April, with select ski areas – those at a high altitude - being able to remain open until June (skilaketahoe.com 2011). Furthermore, demand typically wanes after mid-April throughout the nation, this occasionally forces ski area managers to close before conditions dictate (Scott et. al. 2003, NSAA 2011a).

The final limitation is the claim that potential projected impacts are relatable to all elevations below 3000 masl. This has been refuted through the findings of this study, which has projected far more favourable reductions to ski season length at the higher altitudes of Squaw Valley. Since high altitude operations at Squaw Valley are exceeded in elevation by other ski areas in the state, future ski season length in these locations has potential to be even more favourable. However, as demonstrated in Table 3.2, a large portion of ski areas in the Lake Tahoe region, and thus a large portion of ski areas in California at large, are at a relatively low altitude, increasing their vulnerability to potential climate change.

Overall, it is reasonable to assert that, based on the results of this study, the work of Hayhoe et. al. (2004) over estimates the impacts to future ski operations in California.

Climate change does pose a significant threat to winter alpine tourism in the state, but not to the extent previously projected. The major risks relevant to ski operators through the 2050s will be access to sufficient water and capital resources for snowmaking, not warmer temperatures alone. This will be discussed in further detail in a subsequent section.

Colorado

Colorado's ski industry has been the focus of multiple climate change assessments. The two most prominent reports, Zimmerman et. al. (2006) and Lazar and Williams (2008), have notable methodological limitations that raise questions about their findings.

Zimmerman et. al. (2006) follow Hayhoe et. al. (2004), though their findings are derived exclusively from April 1 snowpack and density, further reducing the validity of this methodology and resultant claims of ski operations under potential climate change. Zimmerman et. al. (2006) indicate that many areas in the Rockies that had snowpack on April 1 during the baseline period lose that snowpack by the year 2085 (Zimmerman et. al. 2006). Most relevant to this work, Zimmerman et. al. (2006) assert that snowpack reductions are estimated at 57% for Eagle County, Co., (Vail ski resort) and 50% for Summit County, Co. (Copper Mountain ski resort) by the year 2085. However, as noted by Scott et. al. (2012b), "while there is substantial loss of snowpack compared with the 1970s, snow depths at all of the 14 study areas exceed 50 cm, suggesting that even without snowmaking, ski resorts at all but three locations would still be operational at the beginning of April" (pp. 211).

Grounded on this April 1 assessment, the authors claim; "winter sports dependent upon snow: down-hill skiing, cross-country skiing, snowshoeing and snowmobiling, are expected to decrease in popularity becoming unviable as soon as 2050" (Zimmerman et. al. 2006, pp. 99). The findings of this study indicate this is highly implausible. Only at the absolute lowest altitude examined between the two ski areas, without snowmaking included, and under the 'most change' scenarios, did projections in this study suggest that ski tourism is greatly at risk from potential climate change. Furthermore, when snowmaking is included in projections, all altitudes at both ski areas, under all climate change scenarios, are expected to maintain at least a 100-day season, suggesting they will remain physically viable.

As noted, only Vail's lowest altitude (2500 masl) without snowmaking is greatly at risk from climate change. Only under A1B climate conditions without snowmaking, did ski season length become reduced below the 100-days indicator. However, at this same altitude, under all climate conditions, but with snowmaking included, ski season length is maintained at least 137 and 138 skiable days. Furthermore, under the 'least change' scenarios even without snowmaking included, ski operations at Vail's lowest altitude will uphold the 100-day rule. Vail's lowest altitude, the mot vulnerable to climate change, is indicative of most low altitude ski areas in Colorado, suggesting the state's ski industry will remain viable.

Looking past these projections at the absolute lowest altitude examined, operations at all other altitudes at both ski areas, with and without snowmaking, uphold both economic indicators examined; the 100-day rule and probability of remaining open during at least 75% of all years in the 30-year period. Findings from SkiSim 2 suggest that Vail's mean and highest altitudes will uphold a ski season between 117 – 163 days without snowmaking, increasing to 159 – 173 with snowmaking. Copper Mountain's ski season length at its lowest altitude without snowmaking under the 'most change' scenarios, is likely to have a 117 – 122 day season, while its highest altitude, without snowmaking, is expected to provide 147 -155 day season. With snowmaking included, these projections increase. When examining the findings for Vail and Copper Mountain, nearly the total altitudinal range of ski areas in Colorado is assessed, allowing these findings to infer potential impacts to the state's ski industry, suggesting most ski areas will remain viable into the 2050s.

When comparing the findings of Zimmerman et. al. (2006) with those in this study, the differences are very apparent. Since Zimmerman et. al. (2006) fail to assess any pertinent ski operations indicators and project impacts to an irrelevant timeframe their work perpetuates the 'doom and gloom' discourse in the media; "Colorado's ski industry is at risk of 'melting away'" (Berwyn 2009). The impact of this could be a reduced demand for ski tourism in Colorado, which would have serious implications for the state's economy due to the regional economic reliance on this industry.

Lazar and Williams (2008) use a Snowmelt Runoff Model and determined that high altitude operations, under natural conditions, will retain snow under all future climate change scenarios while the bottom two-thirds will only retain snow under low emission scenarios by 2100 (Lazar & Williams 2008). Furthermore, by the end of the century the timing of avalanches is likely to vary, occurring between sixteen to forty-five days earlier at the top altitude and twenty-two to sixty-five days earlier at the base (Lazar & Williams 2008). The authors state that avalanches will be more likely to occur during the operational season forcing managers to close operations (Lazar & Williams 2008). Projected reductions to ski season length are not provided, it is difficult to compare their findings against those presented in this research.

Similar to the work of Hayhoe et. al. (2004) and Zimmerman et. al. (2006) these authors do not incorporate operational decision making and adaptation strategies in their appraisal of the Colorado ski industry. The prediction that early onset avalanche occurrence will result in some potential restrictions of season length is valid, however, the omission of proactive avalanche control programs reduces its validity. A common practice amongst ski area managers is to assess the potential for avalanches to occur and proactively trigger them if necessary (Silverton, McIntosh & Kim 2007). This reduces the risk of injury or death from avalanches while allowing operators the ability to manage their hills more extensively (Silverton et. al. 2007). Some ski operators will likely be required to close sections of their skiable terrain earlier than the historic average, however, the proportion is likely to be very small, and it is likely that skiers will simply shift activity to more safe ski areas.

Media

The claims in the media are the most exaggerated regarding the impact of climate change on the ski industry in the western United States. Amongst all sources, the media is the worst culprit for perpetuating the stereotype that climate change will lead to the demise of this industry. On occasion, the media in both case study regions assessed in this work has gone so far as stating that the industry will be obliterated by climate change with captions such as: ‘Climate Change: The End of Sierra Skiing?’ (California) and ‘Colorado’s ski industry is at risk of melting away’. Hayhoe et. al. (2004) is the only known work to date which predicts such drastic impacts; projections to this extreme occur only under the warmest (A1Fi) scenario using a GCM with high climate sensitivity and projected to the year 2100, without snowmaking included.

Citing a (2006) Halifax Travel Insurance report, which identified the Whistler ski area as particularly at risk from potential climate change, Scott et. al. (2012b) note that "there are real dangers with this type of misinformation." (pp. 211). Overtly negative portrayals of ski tourism could serve to influence demand as well as subsidiary economies. The real estate industry has been identified as particularly vulnerable to this manner of impact, as it is now possible to compare ski areas' resilience to climate change in purchasing property (Scott et. al. 2012b). Furthermore, banks and capital investment firms have shown weariness to engage with ski operators as a result of such claims; in Europe, certain banks have restricted financing of low-lying ski areas based on studies that did not include snowmaking and thus overestimated impacts (Scott et. al. 2012b).

When this misinformation is presented in the media it is unlikely that readers will acknowledge the methodological limitations within the studies from which claims are based. As such, impacts such as those listed above will become the perceived reality, which will only serve to aggravate the impacts of climate change.

Reassessment Conclusion

From the above discussion it is clear that previous claims and projections of ski operations under climatically changed futures misrepresent the impacts to be expected. The use of the SkiSim 2 model has shown very different and improved impacts by mid-century to ski operations and reductions to season length in Colorado and California.

Adaptation Potential of Snowmaking

The extent to which the adverse impacts of climate change are experienced depends on location, elevation and the use of adaptation strategies. Snowmaking will be pivotal in sustaining current season length and supplying a ski-tourism product under future climate change scenarios. However, the ability to artificially manufacture snow may be reduced, or even eliminated at certain elevations, due to temperatures exceeding the current technological capacity of snowmaking equipment. This occurs at two-thirds of the ski areas modeled in this study, as Squaw Valley's lowest altitude is likely to become snow deficient under the CCCMA B1, IPSL A1B and MIROC A1B scenarios, as well as Vail's lowest altitude under the 'most change' scenarios.

These findings are supported by Bark et. al. (2010), who determined in Arizona that despite snowmaking remaining a plausible adaptation strategy based on costs and revenues, the technological thresholds are passed under climate change, which will restrict its use in the future (Bark et. al. 2010). Assessing two ski areas in Arizona, the ability to manufacture snow will be limited by the 2050s, becoming seriously jeopardized by the 2080s (Bark et. al. 2010). Artificial snowmaking capacity will be especially hindered in the shoulder seasons, cited as November, December, March and April in Arizona, and will vary greatly between seasons depending on El Nino and La Nina cycles (Bark et. al. 2010).

Reductions to this capacity in November and December will have an increased impact, as artificial snow creation at this point in the season is critical for commencing ski operations before the revenue important Christmas/New Years period. A reduced capacity for snowmaking in March and April is of lesser consequence, as typically a sufficient snowpack is established by these months to sustain operations through the average closing period for ski areas in western North America.

Additives to water for snowmaking are an industry solution to increasing temperatures that are gaining momentum (Peaks to Prairies 2002). These are intended to increase the number of nucleators present in the water so as to "increase the nucleation temperature at which water droplets begin to form ice particles", effectively increasing the temperature at which artificial snow can be created (Peaks to Prairies 2002, 11-7). This will allow artificial snow to be created more economically as temperatures increase under projected climate change, extending its viability as an adaptation strategy further into the future. The use of these products have been met with concern by various environmental advocacy groups and government regulations, restricting their universal application (Scott et. al. 2012b)

In spite of Bark et. al.'s (2010) findings, the use of snowmaking as an adaptation strategy in the future may still be more inhibited by limited economic and environmental resources than changing climate conditions (Scott & McBoyle 2007). The cost of supplying a ski-tourism product and restricted access to sufficient water resources, if operations are reliant on snowmaking, have been identified as primary constraints by Scott & McBoyle (2007).

Economic Limitations

Increased expenses related to snowmaking from infrastructure expansion and increased operating costs are likely to impact ski areas' financial bottom line. Together with potential reduced demand from climate change, these costs may exceed the additional revenues garnered through increased skiable days with snowmaking in place. Thus, costs are likely to further limit the ability of ski areas to employ this adaptation strategy (Scott & McBoyle 2007; Bark et. al. 2010).

Snowmaking costs - both in terms of the total amount and relative percentage of operating expenses - are dependent on the size of the ski area, the proportion of terrain equipped with snowmaking, energy costs, employment costs, and the reliance on snowmaking in supplying a ski product (NSAA 2010). For instance, the Rocky Mountain region, has higher total snowmaking expenses than most other regions in the country, however, as a portion of total operating expenses, these costs are below the national average (NSAA 2010).

As noted in chapter 2, the following snowmaking expense figures (from a single operating season) are only intended to provide a frame of reference for snowmaking costs. Dollar figures do not represent long-term trends, as they have increased over the ten-year period leading to 2010/11 (NSAA 2011c). Also, 2010/11 costs may not be representative of previous years' dollar amounts as this season experienced above average natural snowfall in both the Rocky Mountain region – which received 344 inches of snowfall compared to the 313 inch average over 2007/08-2009/10 period - and Pacific West region – which received 479 inches of snowfall compared to 376 inch average over 2007/08-2009/10 period. This natural snowfall likely reduced reliance on artificial snow production in 2010/11, lowering costs.

In the 2010/11 season, average expenses for snowmaking were $489,000 (USD) at the national level across all respondent ski areas, accounting for 3% of all costs (NSAA 2011c). Upon first appraisal, 3% of total operating expenses is not a significant figure, however, in comparing it to other costs, its significance becomes clear. Nationally, amongst all mountain operations costs (e.g. Snowmaking, lift operations, lift maintenance, ski patrol, grooming, etc.), snowmaking ranks the third largest single expense, following lift operations and lift maintenance (NSAA 2011c). It is the largest single source of expense in the Northeast and Southeast, second largest in the Midwest, seventh in the Rocky Mountain region and eighth in the Pacific West (both Pacific North and Pacific South) (NSAA 2011c).

A detailed breakdown of the associated snowmaking expenses, and how they are accrued, further illustrates the significance of snowmaking as an operating expense, and the potential for increases under future climate change. The cost of power and electricity used for snowmaking accounts for 42% of the total snowmaking expense nationally (NSAA 2011c). Conversely, the energy required for snowmaking accounts for 20% of total electricity and power costs nationally; on average in the 2010/11 season snowmaking cost operators $205,000 in energy alone (NSAA 2011c). This qualifies snowmaking as the largest single source of power and electricity expenses amongst all other ski operations activities (NSAA 2011c). In 2010/11, in the Rocky Mountain region snowmaking accounted for 14% of all energy costs, amounting $164,000 on average amongst resorts (NSAA 2011c). In the Pacific South region, snowmaking accrued 16% of all electricity and power costs amounting $192,000 in 2010/11 season (NSAA 2011c).

Clearly, snowmaking and energy costs are inextricably linked. Increases in either snowmaking capacity or energy prices will multiply total-operating expenses substantially (NSAA 2010). To merely sustain the December 15 – April 15 period, ski areas in the Rocky Mountain region are expected to require an increase in snowmaking capacity by up to 307%, while in Lake Tahoe ski areas are likely to be required to increase snowmaking capacity by up to 281%. The related expenses, outlined above, are likely to increase in proportion to these projected snowmaking requirements.

Exacerbating the issue of potential increases in operating costs from snowmaking is the requisite capital cost of expansion of this adaptation strategy. These two regions each currently have fewer ski areas with some level of snowmaking capacity than any other region. Furthermore, resorts in the two regions examined have the smallest portion of terrain currently equipped with snowmaking. As cited previously, ski areas in the Rocky Mountain region have on average only 12% of terrain equipped with snowmaking, while the Pacific West has only 7% (Pacific South ski areas have 13% snowmaking coverage while Pacific North ski areas have 1% snowmaking coverage on average) (NSAA 2011c). In the future, as ski areas in these regions are required to increase their reliance on snowmaking to sustain operations under warmer climate conditions, they will be required to invest heavily in this adaptation (NSAA 2011c). This alone will serve to eliminate certain ski areas as a result of inadequate financial resources.

Bark et. al (2010) state that “the economics of snowmaking investments hinges on the balance of incremental costs and incremental revenues attributable to a longer and more consistent season” (p. 480). They continue to state that the “spatial heterogeneity of climate change impacts” is already a policy concern for ski areas in western Europe and the northeast United States (Bark et. al. 2010, p 480). Ski area closures to date, as well as projections using the SkiSim 2 model, in the Northeast United States ski region confirm this notion, as larger and higher altitude ski areas are better inclined to absorb the cost of snowmaking investments (Hamilton et. al. 2003, Scott et. al. 2008b, Bark et. al. 2010). In their regional analysis of winter-based recreation in the Northeast USA, Scott et. al. (2008b) determined “it will be the relative advantages of local climatic resources and adaptive capacity by individual ski areas that determine the ‘survivors’ in an era of climate change” (Scott et. al. 2008b, pp. 593). Small, individually run ski areas have been identified as particularly at risk due to inadequate capital resources required for both snowmaking expansion and increased operating costs.

The results of this work suggest the same pattern will emerge in the western United States. The economics of snowmaking investments are of particular concern for ski areas in California, as these tend to be smaller-scale, at lower altitudes and more likely to be reliable on snowmaking in supplying a ski-tourism product in the future (onthesnow.com).

Environmental Limitations

In addition to higher temperatures and economic constraints, the ability to create artificial snow may be limited due to environmental factors and concerns (Scott & McBoyle 2007). Restricted water use as a result of climate change, compounded by increased global population and the subsequent increased water-demand, has been identified repeatedly in the literature as a threat to tourism and its entities (Gossling, Peeters, Hall, Ceron, Dubois, Lehman & Scott 2012, Scott et. al. 2012b). Environmental limitations to snowmaking centre on the availability of water resources (Scott & McBoyle 2007). Both Colorado and California have been identified as regions within the United States at an increased risk to decreasing freshwater reserves (The Wilderness Society 2009a; The Wilderness Society 2009b; Zimmerman et. al. 2006).

Water use for snowmaking varies according to the proportion of skiable terrain equipped for snowmaking and reliance on artificial snow in supplying a ski product (Scott 2005, Gossling et. al. 2012, Scott et. al. 2012b). Estimates of water consumed for snowmaking in France, in 2007, amounted to 19 million m3, while in the USA, during the 2004/05 season, snowmaking used 60 m3 (Gossling et. al. 2012; Badre, Prime & Ribeire 2009, Scott et. al. 2011).

In California, the equivalent of 750,000 families annual freshwater use has already been lost to date due to a 10% reduction in Sierra Nevada snowpack alone (The Wilderness Society 2009a). Projections of future snowpack loss in California, by the 2050s, range 75-90% (Hayhoe et. al. 2004). This reduction is significant when considering that snowpack supplies approximately one-third of all freshwater resources for the state (Hayhoe et. al. 2004; California Department of Water 2012). As temperatures increase, the ratio of rainfall vs. snowfall events will shift to favour rainfall. This is in addition to increased average surface temperatures, which will cause the reduction in snowpack (Hayhoe et. al. 2004). Aside from the relative proportion of water supplied through snowpack, reductions to this supply are concerning since snowpack provides a consistent resource, which is needed in California to offset reduced precipitation in the spring and summer months (Hayhoe et. al. 2004).

In the future it is likely that agricultural, residential and industrial water users will receive a larger portion of allocation rights as these are the backbone of the state's economy (Ackerman & Stanton 2011). Specifically, agricultural and residential allocations are likely to be favoured since they are essential to sustaining life (Hayhoe et. al. 2004; Ackerman & Stantaton 2011). As a result, tourism is unlikely to receive adequate water resources.

Colorado will face many of the same threats and issues posed by climate change as California in relation to water resources. A primary difference between these states is the overt reliance on snowpack and stream flow for water resources in Colorado

(Zimmerman et. al. 2006). As much as 75% of Colorado's water resources flow from snowpack accumulated in the Rocky Mountains (The Wilderness Society 2009b). This is troubling considering that most areas in Colorado could lose upwards of 50% of their snowpack by the 2050s and beyond (Zimmerman et. al. 2006). Similar to California, water resources originating from snowpack in Colorado provide a consistent water supply that is pivotal for agricultural uses. Decreased snowpack and increased events where precipitation falls as rain will result in a greater portion of Colorado's water resources being lost prior to utilization (Zimmerman et. al. 2006).

Agricultural and residential water users in Colorado will be given a majority share of allocations, as these are vital to the sustenance of the state's population and economy. An additional concern noted throughout the literature for Colorado's future water supplies is the use of available water to combat forest fires (Zimmerman et. al. 2006, The Wilderness Society 2009b). A reduction in this supply poses significant threats to other economic activities. In the future it will be an additional factor to consider in allocating water rights.

Tourism in Colorado constitutes as a large portion of the state's economy and its tourism activities are more reliant on available water resources (Zimmerman et. al. 2006; The Wilderness Society 2009b). As such, the literature suggests that tourism must receive an adequate share of allocation rights in the future to sustain the economy (Zimmerman et. al. 2006; The Wilderness Society 2009b). However, because water resources projections are so severe it is unlikely that allocations will suffice for ski operations.

Compounding future water allocation issues, ski areas in both California and Colorado currently have lower than average snowmaking in place. Increasing their snowmaking coverage in present day would require an increase in their allocation rights. Successfully increasing these rights to the requisite level in the future, in line with projected increases in required snowmaking, will become even more challenging given projections of water-supply reductions.

An emerging notion surrounding the use of water for snowmaking is whether this use is actually consumptive of water resources, or instead does this use simply shift its location, both geographically and temporally, in the respective watershed. Estimates have shown that approximately 10% of water used for snowmaking is lost to sublimation and evaporation, however, this value is likely to vary according to regional characteristics (Smart & Fleming 1985, Gossling et. al. 2012). Concerns surround when and where the water is extracted from, if taken from natural bodies of water this could place additional stress on resources. The determination of water for snowmaking placing additional stress on resources has been shown to depend mostly on timing (Vanham et. al. 2009). However, potential impacts will vary according to water resources at the local and regional scales.

Vanham et. al. (2009), analyzed water availability for ski tourism, and specifically the viability of snowmaking, under a 2°C temperature increase climate change scenario in the Kitzbuehel region (Austria). The results of this work indicate that at the regional level no impacts are expected (Vanham et. al. 2009). However, during December resources are likely to become stressed as a large volume of water is required to be extracted for snowmaking at the beginning of the ski season (Vanham et. al. 2009). Additionally, the authors note that impacts are more likely to arise at local, or sub-basin levels as the volume and timing of river flows are expected to shift in such a climate change scenario, stressing current users' allocations (Vanham et. al. 2009). Allocation rights will need to be revised accordingly. The authors stress that ski area operators will need to develop reservoirs to accumulate and store water supplies to overcome shortfalls in allocation rights during pivotal snowmaking periods (Vanham et. al. 2009).

In addition to water reservoirs, ski areas may be required to access water from other sources. Bark et. al. (2010) state that one (Snowbowl) of the two case study ski areas in their report has entered into an agreement with the local municipality to use reclaimed waste-water for snowmaking. This source is intended to provide an adequate supply without impacting regional water table levels, however, it is likely to come at additional transportation and/or infrastructure development costs (Bark et. al. 2010).

As discussed above, chemical agents can be used as additives to water to increase the temperature at which snowmaking can be economically conducted. While this would allow snowmaking to remain a viable adaptation strategy longer into the future, it can be restricted due to environmental regulations governing the use of such agents (Scott et. al. 2012b). This is most likely to arise as an issue at the local or regional level as each jurisdiction that encompasses a ski area will need to determine whether the use of these additives is appropriate or not. This has the potential to restrict the use of snowmaking, likely resulting in regional advantages and disadvantages (Scott et. al. 2012b).

The use of snowmaking may be further limited as the source from which water resources are extracted may be contaminated. In turn, using this water for snowmaking will distribute these contaminants over a broader area with the potential to negatively impact surrounding ecosystems (Hyrdosphere Resource Consultants, Inc, 2001). While this issue is relegated to select areas – particularly those with a previous history of mineral mining - and the rate at which contaminants are dispersed is likely to vary according to reliance on snowmaking, there is the potential it could eliminate snowmaking as an adaptation strategy (Hydrosphere Resource Consultants, Inc, 2001).

These factors will also impact revenues as operators may be required to: pay for adequate allocation rights, construct reservoirs to store water or purchase this resource elsewhere (Scott & McBoyle 2007; Bark et. al. 2010). It is possible that these economic and environmental forces will serve to negate snowmaking as an adaptation strategy prior to the technological thresholds being exceeded.

Redistribution of Market Share From Climate Change

As proven through the results of this study, areas of the Pacific West region are more vulnerable to climate change while areas within the Rocky Mountain region are less vulnerable. Looking more broadly, other national and international ski regions are also projected to be more or less vulnerable to climate change (Scott et. al. 2003 Scott et. al. 2006, Scott et. al. 2007, Scott et. al. 2008b, Pickering & Buckley 2010, Steiger 2010, Steiger 2011). As a result of these differences in projected impacts, a redistribution of the market share is likely to occur between local, regional, and international ski markets Scott et. al. 2012b).

Based on the results of this study, minimal redistributions can be expected within Colorado as ski areas are projected to be resilient to climate change with sufficient snowmaking in place. Despite the finding that they are likely to lose a portion of their skiable days, both ski areas, at all elevations examined with snowmaking included, can sustain a sufficient season length (>100 days). Encouragingly, the results of USA demand-side studies suggest that the majority of participants will either ski with the same frequency, ski more intensely throughout a shortened ski season, or will wait for appropriate conditions to ski (Vivian 2011, Dawson et. al. 2011).

Potential shifts in demand for skiing are likely to favour those ski areas at a higher average altitude due to the improvement in projections with increasing altitude. At higher altitudes ski areas are likely to sustain a greater portion of their baseline ski season length while being less reliant on artificial snow. Reliance on artificial snowmaking in supplying a ski product is likely to be particularly relevant for Colorado ski areas due to reduced projected impacts. Lastly, Dawson et. al. (2009) found that the size of a ski area may affect redistributions. In their analogue analysis, medium and large sized resorts benefited, while small and extra-large sized resorts recorded either no difference or decreases in visitation. Potential shifts due to these factors is supported through Vivian (2011), who determined that if presented with snow-poor conditions, 23-30% of skier respondents would be willing to travel further within the same region to satisfy their demand.

California is more likely to experience intra-state redistributions of market share as a result of projected climate change, primarily the result of elevation. In modeling ski operations at Squaw Valley, its minimum altitude does not meet the minimum season length requirement for profitability in any scenario without snowmaking. Even with full snowmaking capacity, the 100-day rule is only upheld in the two 'least change' scenarios, while the minimum (75% of all years) probability of remaining open during the Christmas/New Years segment is only met under the GISS B1 scenario (Scott et. al. 2008b). Together, these reduce the likelihood of ski operations at low altitudes remaining possible, thus likely resulting in an increase in market share for high altitude operations.

Further supporting the notion that high altitude ski areas' are likely to benefit from an increase in market share is their inclusion in ski conglomerates. Similar to subsidiaries of the Vail Resorts Management Company in Colorado (Vail, Beaver Creek, Keystone, Breckenridge), those ski areas in California (Northstar, Heavenly, Kirkwood) that are incorporated into conglomerates are also likely to be less vulnerable as they are better posed to absorb the potential impacts of climate change due to their capital resources (Scott & McBoyle 2007). This will afford them the ability to better adapt, namely being able to expand snowmaking. This will be a pivotal distinction in California as projections of both ski season length reductions and snowmaking requirements are severe. The state's smaller, individually operated ski areas are at a greater risk as a result of their exclusion from conglomerates, requiring them to bear the additional costs of snowmaking expansion and energy costs alone.

Proximity to major urban centres is likely to be another important distinction for ski areas in Colorado and California. While this may play a lesser role when looking at long-term periods of market redistributions (e.g. over the entire 2050s period), Steiger 2011 found that during the particularly snow deficient 2006/07 season a ski area located nearest Innsbruck (Austria) benefited (+11% visitation) from poor conditions in surrounding locations. In the Lake Tahoe ski region, this is likely to be most relevant as the ski areas identified as less vulnerable above - those at a higher average altitude and incorporated into a conglomerate - are also located most closely to large urban centres.

Moving past state level changes, there are likely to be more pronounced inter-regional redistributions to skier markets as a result of diverging impacts to ski operations from projected climate change. When looking at the USA, the Rocky Mountain region is most likely to benefit from such redistributions due to more extensive impacts in southerly, coastal or low altitude ski regions. This suggests a shift in skier visits from the Pacific West, Northeast, Southeast, and Midwest regions. Vivian (2011) found that between 8-11% of skier participants in the Northeast would travel outside of this region if ski conditions degraded past critical thresholds locally. This is a substantial number of skier visits when considering that in the 2010/11 season the Northeast ski region recorded 13.8 million skier visits (NSAA 2011a). However, the limitations to demand-side assessments' methodology obscure predictions as they provide little insight into the number of skiers visits likely to be maintained and where.

Within the Rocky Mountain region, Colorado ski areas are likely to receive a large portion of visits due to the diversity of ski areas within the state. However, ski areas in Utah, Montana, Wyoming, Idaho, and throughout the Canadian West (Alberta, British Columbia), can expect an increase in visitation. These latter states and provinces may experience an even larger influx of visitors if substantial climate change occurs due to their northerly locations (Scott & McBoyle 2007). Ski areas located in more northerly latitudes are projected to be more resilient to climate change - despite warming temperatures, climate conditions are likely to remain within a range still conducive to providing ski operations - thus likely to benefit from a shift in demand (Scott & McBoyle 2007).

Additionally, increased skier visits to North America is likely to occur due to disruptions to ski operations in international ski regions. The Rocky Mountain and Canadian West ski regions are again likely to benefit most. For instance, during the 2006/07 season European skier visits in the Rocky Mountain region increased substantially because of poor local conditions (Scott et. al. 2012b).

Continental and international shifts in market demands may also favour those ski areas located in close proximity to major urban centres or transportation hubs. This is mainly due to the ease with which travel and participation is made possible. However, such patterns may emerge as it has been found a significant portion (20-30%) of visitors to Canadian ski resorts did not ski during their visit, proximity to major urban centres increases the diversity of tourism pursuits available, potentially increasing motivation for travel (Scott & McBoyle 2007; Williams & Dosa 1990)..

Ski Industry Comprehensive Planning Approach to Climate Change

A comprehensive planning approach to climate change by ski operators has been recommended in multiple academic appraisals of climate change and the ski industry (Scott & McBoyle 2007, Scott et. al. 2008b, Bark et. al. 2010; Steiger 2010). The creation of 'winners and losers' from climate change is dependent on more then the adverse impacts likely to be experienced at various destinations (Scott et. al. 2008). It is also affected by a destination's adaptive capacity, the utilization of appropriate adaptation strategies and by the impacts and actions of a destination's competitors (Scott et. al. 2008a). It is imperative that ski areas create localized approaches to mitigating the adverse impacts from projected climate change (Scott & McBoyle 2007, Scott et. al. 2008b, Bark et. al. 2010). As outlined by Bark et. al. (2010), successfully coping with climate change throughout the ski industry will depend on the following factors:

- The relative impact of climate change on the resort and its competitors;
- The costs of additional snowmaking;
- Participant's response to degraded conditions;

- The impact of other adaptation strategies, such as business diversification, weather insurance and derivatives;
- The redistribution of market share based on intra and inter-regional impacts and increased costs from adaptation;
- The resort's ability generate sufficient revenues despite the above concerns

As discussed throughout the report, snowmaking will be pivotal in retaining the ability to supply a ski-tourism product. The ability to better predict season length and visitation will be important in overcoming the additional costs associated with snowmaking. If snowmaking systems are employed now, when visitation patterns are still regular and predictable, costs will be incurred at a time when earnings are still high (Bark et. al. 2010). This opportunity may be lost in the future if the expansion of these systems is delayed. To fully utilize this adaptation strategy ski area operators must also consider and plan for adequate water resources.

By implementing snowmaking now, before it is necessarily required, a resort's image will be improved because it will possess the ability to provide consistent ski season length with reliable conditions. Putz, Gallati, Kytzia, Elsasser, Lardelli, Teich, Waltert and Rixen (2011) found that 88% of respondents at Swiss ski areas considered snow reliable conditions regardless of natural or artificial snow as very important to destination selection. Respondents also indicated they were supportive of snowmaking to increase the quality of terrain conditions (Putz et. al. 2011). In this regard, a resort is more likely to have sustained visitation into the future if it is considered to be snow-reliable (Scott et. al. 2008b). Regardless of actual conditions, participants may be more willing to travel to a destination if they have had positive experiences in the past and perceive a ski hill to have reliable conditions (Scott et. al. 2008b; Hamilton et. a. 2003).

Ski operators have identified other adaptation approaches as "incremental adjustments of existing strategies" to business development and climate variability in the future (Scott & McBoyle 2007). Two prominent examples are the formation of ski conglomerates and the diversification of revenue streams (Scott & McBoyle 2007).

The creation of ski conglomerates is currently underway throughout North America (Scott & McBoyle 2007). It allows operators to increase their revenues, capital and market resources to increase their competitive advantage (Scott & McBoyle 2007).

While conglomerates may not be a direct response to climate change, they will likely prove to be “the most effective adaptation to future climate change.” (Scott & McBoyle 2007, pp. 1420). A key facet of developing ski conglomerates is acquiring property in multiple locations. This can be seen as a sort of insurance, as poor ski conditions and lost revenues in one region, can be offset by average or above average performance in another (Scott & McBoyle 2007). This will serve to increase the likelihood of net revenues each season. Additionally, the financial impact of poor conditions and infrastructure expansion can be spread throughout the organization, which is likely to have higher capital resources, increasing the overall level of adaptive capacity (Scott & McBoyle 2007).

It is advised that ski conglomerates incorporate ‘beginner’ skill level skiable terrain amongst their destinations to encourage and sustain new participation in the sport. This can be achieved either through acquiring existing family-friendly ski areas or through slope development at existing resorts. Regardless, this will be essential to promoting participation amongst non-skiers, and sustaining visitation into the future (Won, Bang & Shonk 2008, NSAA 2011a)

Diversifying revenue streams is another effective approach to increasing the likelihood of successfully coping with climate change. Operators commonly diversify revenues through providing accommodations, lessons, rentals, food and beverage services and entertainment (Scott & McBoyle 2007). The latter of these options are important given the proportion (20-30%) of visitors to ski areas who did not participate in skiing (Scott & McBoyle 2007; Williams and Dossa 1990). Alternative activity offerings include snow tubing and dogsled rides, along with other more passive activities such as spa retreats. Offering alternative activities to this cohort will capitalize on lost revenue and increasingly separate successful and unsuccessful operators. (NSAA 2010; Scott & McBoyle 2007).

Most importantly, ski operators must continue to diversify their product offerings through summer activities (Scott & McBoyle 2007). These activities could include golfing, horseback riding, water activities, hiking, camping, amongst other localized options. However, it has been noted that revenues generated through spring, summer and fall visitation will not be enough to offset lost revenues in winter tourism (Scott et. al. 2012b). Ski resorts will need to continue to position themselves as ‘four season resorts’ in order to generate revenues for the entire year (Scott & McBoyle 2007). Skiers and snowboarders have a high level of adaptive capacity to climate change since they have the ability to alter the specifics of their travel patterns (Scott & McBoyle 2007). The development of four season resorts may also increase loyalty, or encourage property holdings, for a particular ski area, which may reduce potential shifts in market demand as a result of climate change (Dawson et. al. 2011).

The main advantage of these approaches, from a ski operations perspective, is the increased likelihood of absorbing any additional costs from expanding snowmaking capabilities. This will also serve to reduce the degree to which additional costs are passed onto users, increasing the likelihood of maintaining visitation (Steiger 2010, Bark et. al. 2010). Pricing is a critical issue that must be addressed in any comprehensive planning approach to mitigating the adverse impacts from climate change. In Unbehaun et. al. (2008) a 10% increase in total trip costs was identified as the threshold which ski participants are willing to incur to participate. If snowmaking costs are transferred to participants it is likely that a proportion of skiers would select alternative, naturally snow-reliable destinations, or cease participation altogether (Bark et. al. 2010; Scott & McBoyle 2007). This could have disastrous effects on the future of the ski industry if new participants to these sports are eliminated as a result (Bark et. al. 2010). Options for pricing may include incentives or guarantees, whereby resorts provide discounted rates or reimbursements if conditions are degraded (Scott & McBoyle 2007).

6. Conclusion

This study employed the SkiSim 2 model, a locally calibrated, semi-distributed ski operations model, to determine the potential supply-side impact of climate change on ski areas in Colorado and California. The principal goal was to determine potential reductions to ski season length, including impacts to revenue important season segments, as well as the efficacy of snowmaking in mitigating losses.

The SkiSim 2 model was shown to perform well for the three case studies selected for this research, as evidenced by its ability to model historical snowfall, snowmelt and baseline (1961-1990) ski season length. For the Tahoe City climate station SkiSim 2 modeled no difference in snowfall days when using either historical climate data or data produced by LARS-WG. When using historical climate data it measured the potential for 103 skiable days while modeling 104 with data generated by LARS-WG, a 1% difference. Conclusively however, SkiSim 2 modeled baseline natural season length for Squaw Valley at 138 days, under natural conditions, increasing to 153 days with snowmaking, when averaged across the lowest, mean and highest altitudes. This compares to an average season in the baseline period lasting approximately 150 days (mid-November to mid-April). These differences were deemed acceptable, and thus SkiSim 2 was able to model actual ski conditions well for the Tahoe City climate station.

For the Vail climate station SkiSim 2 measured 188 days with snowfall using historical climate data while modeling 172 days using data produced by LARS-WG, an 8% difference. SkiSim 2 measured 132 skiable days using historical climate data, however it modeled 117 when using LAR-WG produced data. The larger differences within the Colorado numbers are attributable to the increased average elevation of mountains in Colorado, these topographic features increase the presence of micro-climates. Baseline average ski seasons typically last between mid-November to mid-April in Colorado, SkiSim 2 modeled a natural ski season length ranging between 145-159 days, increasing to 171-173 days when snowmaking is included, between the two Colorado case studies examined. The larger discrepancies between historical average ski season length and baseline season length modeled by SkiSim 2, when inclusive of snowmaking, is reflective of the low snowmaking coverage at these ski areas. Again, SkiSim 2 was deemed able to model ski conditions for the Vail climate station well.

Consistent with other North American and western European studies that used the SkiSim 2 model, snowmaking has been shown to substantially reduce climate change risks amongst the selected ski areas. Nearly all elevations under all future climate scenarios at each ski area assessed in this study have been predicted to maintain viable ski seasons when snowmaking is included. Only at the lowest altitude at Squaw Valley is season length reduced to an unviable level (<100 days), even then with snowmaking included this only occurs under the 'most change' scenarios.

Squaw Valley's lowest altitude is most vulnerable to potential adverse impacts from climate change. At this altitude, under natural conditions, ski season lengths will not uphold the 100-days in any future climate scenarios. With snowmaking, projections improve as the minimum ski season length requirement is met in each of the B1 emission scenarios, though still not being met under A1B emission scenario conditions. Furthermore, the economic indictor of the probability of remaining open during the Christmas/New Years segment, with snowmaking included, is only met in the GISS B1 scenario. Lastly, at this altitude of Squaw Valley the capacity to produce artificial snow throughout the entire season is surpassed by the requirement for artificial snow during the December 15 - April 15 period. Together, losses to ski season length during key revenue generating periods, combined with snowmaking being an unviable adaptation strategy, render ski operations at this altitude most vulnerable.

There is a substantial improvement to projections when examining the mean and highest altitude. At the mean altitude, even without snowmaking included, the 100-day rule can be upheld in all but the MIROC A1B 2050s scenario. With snowmaking included, this rule is met under all future 2050s climate change scenarios. The criterion for remaining open during the Christmas/New Years period is met in all but the IPSL A1B scenario. Under B1 emission scenario conditions the findings suggest that revenues are likely to remain into the 2050s, however, if A1B emission scenario conditions occur some loss to revenues is likely. Projections of snowmaking production and the requirement for artificial snow are also improved relative to the minimum altitude; the findings suggest snowmaking will remain a viable adaptation strategy to climate change in the 2050s for the mean altitude. Continuing these improvements, all pertinent performance indicators are met at the highest altitude, both inclusive and exclusive of snowmaking.

Due to their higher average elevation, both ski areas in Colorado are likely to remain viable into the 2050s regardless of projected climate change. Without snowmaking at Vail's lowest altitude, the 100-day rule is met under all B1 emission scenario conditions, however, not under A1B emission scenario conditions. With snowmaking this indicator in met under all future scenarios for all altitudes of Vail ski area. Furthermore, it is met without snowmaking at the mean and highest altitude. Also, the probability of remaining open during the Christmas/New Years period for 75% or more of the years during the 2050s is met in all scenarios at all altitudes. Together these suggest a high level of resilience to climate change. Of concern however, Vail's snowmaking projections under the A1B emission scenarios at the lowest altitude do suggest that this strategy may become unviable by the 2050s assuming current technological capacity persists. All performance indicators are met at Vail's mean and highest altitudes, as well as being met at all altitudes of Copper Mountain.

This study's findings were used to reassess previous claims in the academic literature and media with regards to future ski operations and climate change in the western USA. When using a ski operations model, previous claims of the climate change impact on ski tourism in the western USA have only been substantiated at the lowest altitude of select ski areas under select climate scenarios. Furthermore, similar projections have only occurred when snowmaking is not incorporated. It has been determined that the majority of previous claims over estimate the impacts to ski operations from climate change. These ill-informed claims are likely to adversely affect perceptions of the ski industry in these locations under climate change, potentially impacting visitation, revenues and damaging dependent auxiliary businesses. Such inaccurate portrayals must be overcome to best position this industry to be resilient to climate change.

While snowmaking has been shown to vastly improve the outlook for ski operations under a climatically warmer future, especially for California ski areas, its use may be limited. Aside from its application being restricted due to warming climate conditions, there are economic and environmental constraints of its application.

Snowmaking is a costly application, one that requires substantial investment in infrastructure as well as increased energy costs. This will likely eliminate it as a viable adaptation strategy for certain ski areas as the initial investment may be unaffordable or because the revenues generated through sustained ski season length may not offset the increased costs. Large, high altitude ski areas, and those accompanied to a ski conglomerate are best suited to absorbing the additional costs associated with snowmaking.

The environmental limitations to snowmaking surround the availability of water resources. Fresh water resources have been identified as at risk of being depleted due to climate change. Subsequently, snowmaking as an adaptation strategy may be limited, as ski areas may not be allocated sufficient resources when competing with other water intensive activities such as industry, agriculture and residential uses. This limitation is likely to vary on a case-by-case basis, depending on local water resources and projections of water supply loss.

The key findings from this research surround the notion that ski areas in Colorado, as well as those at higher altitudes, are less vulnerable to season length reductions and less likely to be reliant on snowmaking in supplying a ski product. As a result, ski operations under these criteria are more likely to benefit from a redistribution of market demand. Certain ski areas, or more broadly ski regions, are likely to see an influx of skier visits as conditions in other ski areas/regions decline. Considering the above projections of impacts to ski operations, in tandem with the limitations of snowmaking, ski area managers will need to adopt a localized, comprehensive climate change strategy to mitigate potential adverse impacts.

Future Research Needs

While this research provides important new insights into the potential impacts of climate change on ski operations in Colorado and California, additional insight into the relationship between future climate change and ski tourism must be sought.

The most explicit future research need is the diffusion of similar studies throughout the Rocky Mountain, Pacific West, Midwest and Southeast USA as well as in western Canadian ski regions. As proven, potential impacts to ski operations from climate change will likely be very localized and dependent on a range of climatic and topographic factors. As such, conducting multiple assessments will be the most effective way of gaining a better understanding of the impact climate change will have on the ski industry in North America. This will further the understanding of supply-side impacts to the North American market at large, and only serve to increase the likelihood of sustaining a successful ski industry throughout the coming century.

Gaining a better understanding of the demand-side adaptations in light of projected climate change is cited ubiquitously throughout the climate change and winter alpine tourism literature (Konig 1998, Burki 2000, Scott et. al. 2003, Scott et. el. 2006, Scott & McBoyle 2007, Scott et. al. 2008b, Bark et. al. 2010). Regional demand studies are critical to understanding and/or projecting likely shifts in market demand. These studies must be dispersed throughout multiple regions, assess varied timeframes and conditions to provide operators the requisite insight for comprehensive planning. It would be invaluable to assess responses across the North American market at large, this need centres on the ability to understand how tourists will alter their travel patterns, destination and activity selection resulting from climate change (Scott et. al. 2008b).

To further strengthen findings from both ski operations modeling and assessments of demand-side responses to climate change, analogue assessments of ski operations under climatically atypical years will continue to be needed. Since these provide insight into both supply and demand side impacts, they can be used to validate findings in either of the above research methodologies to gain an even more accurate appraisal of the likely impacts from climate change. Furthermore, continual analogue studies will provide a more detailed understanding since impacts incurred during individual, or short-term (1-3 seasons) periods of snow deficient conditions are more likely to impact the sustainability of the ski industry more than average change sustained over a 30-year timeframe (Scott et. al. 2012b). Important insight into the future of the industry can be gained by analyzing ski areas' performance during these analogue seasons.

The diffusion of further studies examining the sustainability of snowmaking – considering the economic, climatic and environmental feasibility of this adaptation strategy – will also provide a more clear understanding of likely residual impacts from climate change. Such feasibility assessments will provide insight into the likelihood of snowmaking being a suitable adaptation strategy, these studies would serve to better inform ski area managers of the dangers posed by climate change.

Lastly, future research must consider the impact of shortened ski seasons, including delayed openings, closures during key revenue season segments (Christmas/New Years & School Holidays) and early closures, on regional real estate markets. Often, ski areas stimulate real estate development in the surrounding communities. A more thorough understanding of the regional economic impacts of shortened ski seasons will provide a more thorough understanding of the impacts of climate change.

Broadly, research efforts need to address the range of impacts and adaptation strategies in multiple locations to gain an understanding of how the ski industry is likely to evolve in light of projected climate change. Together, enhanced understanding of the relationship between local climatology, ski operations, and the influence of climate change, will only increase the likelihood of this industry remaining viable in the future.

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