Chapter 1: INTRODUCTION

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Long-term measurements of air temperature, sea surface temperatures, and patterns of polar ice mass all confirm the intense warming of earth's climate over the past 60 years (fig. 1). Scientific consensus that fossil fuels contribute to global climate change comes from a combination of physical system science, long-term measurements of temperature and atmospheric CO_2, and paleoproxy reconstructions of past climate. While the global patterns of climate change have been discussed for decades, positive and negative consequences of climate change have recently become more obvious. Examples include: Sea level rise in certain portions of the globe threatens communities and agriculture (IPCC 2014, AR5); Arctic villages near seacoasts are being undercut by wave action as permafrost thaws and coastal geography changes (Alaska Department of Environmental Conservation 2010); Increased CO_2 and lengthening growing seasons have increased agricultural productivity for some crops in some locals (Rosenzweig and Hille 1998).

As the potential consequences of rapid, directional climate change become more apparent, individuals, communities, and nations have begun to consider what actions to take – often called "climate adaptation" – in response to changing climate. Likewise, land and resource management agencies are developing responses to perceived threats to resource values. Coordinated, effective action, however, requires understanding how the physical and biological environment will respond to climate change and how those biophysical changes will affect ecosystem services. This report, crafted as a climate vulnerability assessment (Glick et al. 2011), represents an important step toward developing effective climate change adaptation for land and resource management agencies, and the public, associated with the Kenai/Chugach region of south-central Alaska. Our goal is to examine the potential response of several important features and resources of the Kenai/Chugach region to changing climate over the next 30 to 50 years and to consider the potential consequences of those changes for associated social and economic systems.

Focus of Assessment

A climate vulnerability assessment can best aid resource managers and society in making decisions when it is focused on important ecosystem services (Millennium Ecosystem Assessment 2005). Ecosystem services are the benefits people obtain from ecosystems such as food, clean water, timber, regulation of floods, outdoor recreation, and spiritual values associated with environments. How will changes in the delivery of ecosystem services, changes in the availability of resources, and change in physical conditions experienced by individuals and communities influence the lives of people in the immediate and distant future? The Kenai/Chugach assessment area occurs in a region undergoing change as a consequence of major ongoing physical dynamics – tectonics, glaciation, and extreme snowfall (fig. 2).

Regardless of any climate forcing by industrial society, these dynamics result in significant directional change that will influence social decisions. As will be outlined below, ice sheets have been receding for millennia and mega-earthquakes have periodically stirred the landscape – the Kenai/Chugach is a landscape whose very essence is change, and much of that change is directional at the scale of the entire assessment area over any reasonable time frame. Understanding the potential consequences of climate change demands considering the potential influence of human-caused (greenhouse gas induced) climate change in the context of an inherently dynamic region regardless of human-induced climate forcing.

Two features of this assessment define the scope of this product. First, unlike many vulnerability assessments that focus on natural resource management, this document evaluates several social and economic outcomes of climate change– this broadens the scope of the product. Second, rather than examining a plethora of resource elements we limit our discussion to six broad areas that are of particular concern to people of the region – this limits the scope of the product.

This assessment is written with the goal of providing information that will inform decisions by resource managers and the public. It addresses six topics of keen interest to natural resource managers in south-central Alaska: 1) Snow and ice (glaciers and ice fields), 2) Coasts and Seascapes, 3) Salmon, 4) Vegetation, 5) Wildlife, and 6) Infrastructure. The assessment begins by asking how a changing climate may influence particular physical and ecological features across these topic areas. The consequences of climate change are examined from the perspective of scenarios – potential futures. The assessment then attempts to ask how climate driven changes in the physical/ecological characteristics of south-central Alaska might influence several ecosystem services and associated economic activities. Integrating potential social/cultural consequences into the assessment is an important but difficult task because of the inherent uncertainty in climate scenarios and the response of physical/ecological elements. However, considering potential social and economic outcomes, even in light of considerable uncertainty provides managers a view through a different lens that informs prioritization of adaptation options.

Limiting the set of assessment topics helped authors explore particular resources and ecosystem services more deeply. However, bounding the assessment necessarily left many important topics unaddressed. We considered this outcome desirable because this vulnerability assessment is seen as an initial examination of the consequences of changing climate and anticipates future assessments exploring topics more deeply depending on the needs of managers and the public. Therefore, this is the first step in an iterative collaboration among resource managers and scientists intended to begin understanding the complex outcomes of changing climate.

Constraints on the Assessment

History of the Assessment

This assessment began with a desire by the Chugach National Forest to understand how climate change may be influencing the resources managed by the Forest and the users of the vast landscape administered by the Chugach. Recognizing the importance of understanding potential social, cultural, and economic consequences of biophysical changes occurring on the land, the Chugach partnered with University of Alaska's, Institute of Social and Economic Research (ISER) to produce a modest, narrative report integrating biophysical, social, cultural, and economic consequences. Soon other agencies heard of the effort and an interagency effort developed with an all-lands perspective extending from the western Kenai Peninsula eastward through the Copper River delta region. This organic development brought together a rich array of scientists and practitioners excited about collaboration.. The resulting assessment benefits from the breadth of perspectives and expertise, from the expanded geographic scope, and from the integration of scientists with practitioners. Readers will recognize variation in tone and style in the document that result from the diversity of participants in our collaboration. We offer the document as a tool for learning about climate change in a portion of Alaska from a range of perspectives.

Uncertainty In A Resource Planning Environment

Resource management requires the art of taking action despite uncertainty. Limitations of knowledge, temporal and spatial variation in resource conditions, uncertain socioeconomic dynamics, and limited understanding of future resource needs, all contribute to an environment of uncertainty. As a result, resource managers have developed planning approaches that aid in identifying acceptable decisions in the face of uncertainty (fig. 3).

Climate change adds to the uncertainty associated with natural resource decision making. Furthermore, several features of climate change differ from most factors leading to uncertainty in resource management. Climate change is global, it is long-term, and it cannot be managed directly nor effectively through local or regional action. Consequently, the tools to address uncertainty in most natural resource planning problems may not be effective to address uncertainties associated with climate change. For example, adaptive management (Walters 1986) is a planning tool advocated as a device to address uncertainty in natural resource management (Julius et al. 2013, Tompkins and Adger 2004). Active adaptive resource management employs models to identify dominant uncertainties, develops management experiments to examine those uncertainties, and relies on feedback to gain knowledge and revise management to more effectively meet management goals (Walters 1986). However, the long-term nature of climate change suggests that feedback from management experiments will likely occur too slowly to improve management decisions.

As an alternative, some practitioners suggest that scenario planning may be more effective, and a rich literature is developing around this approach (e.g. Knapp and Trainor 2013, Peterson et al. 2003, Rickards et al. 2014). Understanding the use of scenarios in planning may be illustrated most easily through an example from every-day life. Decisions regarding the purchase of insurance, such as life insurance or home insurance, illustrate the pragmatic use of scenarios in planning. When considering the purchase of life insurance most people envision several potential futures, each representing a different 'story' describing what may happen in the future. None of the stories are 'forecasts' and often the probability of one or another is unclear. The ultimate decision regarding purchase of the insurance policy occurs after integrating the insights that come from considering the various stories. Understanding of probabilities plays a minor role in the decision because management of risk is the actual goal. Instead, the insights generated by the scenarios result in thinking that would not occur otherwise. The use of scenarios in resource management in the context of climate change is very similar.

In this assessment we use the philosophy of scenario planning to help decision makers and the users of public lands make better choices despite the uncertainty of how resources, ecosystem services, and other characteristics of south-central Alaska will change as a result of changing climate. We develop 'story lines' outlining the potential conditions that will be experienced in the future. These stories are intended to motivate innovative thinking about the interaction between decisions and future conditions. Therefore, when we describe potential snow conditions or stream-flow, we are not making forecasts or projections. Rather, we use an understanding of the current physical and ecological system, along with background on history and current trends, to paint a picture, or scenario, that is one plausible rendering of the future. That scenario is neither the only, nor the 'best' illustration of the future. The value of the scenario is in the degree to which it helps the reader recognize that the future will be different than the present (possibly similar to a subset of scenarios), and therefore planning must consider potential alternative futures.

Our approach to scenarios begins by examining a range of climate trajectories that in turn generate several climate scenarios. The entire assessment builds on these climate scenarios. Because the various chapters examine different physical and biological resources, and ecosystem services, each employs the climate scenarios differently. However in all cases, the intent is to stimulate an analysis that considers potential outcomes in a changing landscape. In many cases we illustrate only one scenario – one potential future. When it is employed, this single scenario approach is chosen for simplicity and clarity in communication.

Temporal Scale and Uncertainty

Employing scenarios to examine climate change necessarily requires consideration of future conditions. Climate change models can produce non-intuitive shifts in uncertainty as scenarios are considered for different periods in the future. In this assessment we explicitly consider scenarios in the context of agency planning horizons; planning generally covers 10 to 20 years, but considers the legacy left to future generations. Hence we examine outcomes in the next 10 to 20 years, but also conditions 50 years in the future. How these time horizons influence uncertainty is a bit complex but we outline the basics here.

Our assessment employs downscaled projections from climate models as a foundation for developing physically consistent, place-based scenarios for the future (see Chapters 2 and 3 along with Appendix 1 for more details). The downscaled projections for regions such as south-central Alaska, which experience high inter-annual and decadal variability, tend to result in significant uncertainty for the first 10 to 20 years of projections, higher confidence for the next 30 years or so, and less certainty after 50 or 60 years (Hawkins and Sutton 2009). In some cases, the near-term uncertainty (first decade or two) results from what might be called model 'wind up'. The downscaled model develops a set of initial conditions or a baseline as it begins – this results in an initial climate that is different than what actually occurs (due to regional climate variability, for example) and thus 'uncertainty' in the results. Following this 'wind up' period, these models tend to produce more stable results based on the basic responses of the general circulation model (GCM) that forms their backbone, and the largest source of uncertainty is model-to-model parameterization (for example, the ways internal feedbacks are handled or the fundamental temperature sensitivity to greenhouse gas concentrations). After 50 years or so, however, uncertainty in social (government policy) response to climate change begins to become a major driver in the outcome of the GCM's (due to the magnitude of greenhouse gas emissions) and therefore uncertainty increases. Additional uncertainty that results from 'model uncertainty' is described in more detail in Appendix 1. In this assessment, we explicitly address uncertainty by considering the time scales important to decision making and using them to calculate future scenarios that are resilient to the uncertainty associated with decadal climate variability and model variability (Littell et al. 2011, Snover et al. 2013).

Characteristics of the Chugach National Forest and the Kenai Peninsula Assessment Area

Climatic Setting

The climate in South-central Alaska is subarctic with short, cool summers and long winters. Cloud cover is frequent through the summer, particularly after mid-June, and temps rarely exceed 26.7°C (80°F). Winter snowpack, even near sea level, can extend from October through May. Winters have periods of deep cold but also periods with temperatures well above freezing. Extensive coastline, in combination with complex topography resulting from mountain ranges extending north-south and east-west, result in extremely complex weather patterns and a mixture of continental and maritime influences. Precipitation, snowpack, and temperature maps in Blanchet (1983), along with climate descriptions in Davidson (1996) and DeVelice et al. (1999), provide some detail regarding differences in climate among three portions of the Kenai/Chugach assessment area.

In the Kenai Mountains portion of the Kenai Peninsula, the climate is transitional between maritime and continental, with mean annual temperatures of 3.9°C (39°F) at low elevations and -6.7°C (20°F) at upper elevations. The annual precipitation ranges from 50 to 200 cm (20 to 80 inches) with a mean maximum snow pack of 50 to 300 cm (20 to 120 inches), depending on elevation and location. Climate at the Cooper Lake Hydroelectric Project weather station on the Kenai shows a decline in monthly precipitation from January through June followed by an abrupt increase in precipitation from July through September.

There is a brief period of relative drought in June. This dry period reduces fuel moisture and increases fire frequency in the Kenai Mountains.

Storm tracks tend to move in a counterclockwise pattern from the Gulf of Alaska into Prince William Sound, resulting in abundant precipitation and cool, but not cold, temperatures. The lands around Prince William Sound feature mean annual temperatures ranging from 4.4°C (40°F) at shoreline to 0°C (32°F) at upper elevations. Mean annual precipitation ranges from 200 cm (80 inches) at sea level to over 760 cm (300 inches) at some upper elevation locations. The mean maximum snow pack ranges from 150 to 400 cm (60 to 160 inches) depending on location and elevation. Precipitation at the Main Bay weather station in the Sound exceeds 200 mm (8 inches) for each month of the year.

In the Copper River Delta area, mean annual temperature varies from 1.1°C (34°F) to 5.6°C (42°F). Average precipitation ranges from 200 cm (80 inches) at the seashore to 500 cm (200 inches) further inland. The mean maximum snowpack ranges from 25 to 200 cm (10 to 80 inches) with depth increasing with distance from the seashore. Strong continental winds, which drain the Alaska interior in the winter, flow out the Copper River Canyon, cooling the temperatures in this area. Climate at the Cordova FAA weather station is similar in overall pattern to Main Bay in western Prince William Sound. However, monthly precipitation at Cordova FAA ranges between 125 to 450 cm while it is between 250 to 650 cm at Main Bay, demonstrating the increased precipitation further in the Sound.

The northern portion of the assessment area represented by the high Chugach and Saint Elias mountains, features cold, wet summers and winters. The annual precipitation occurs mainly as snow at elevations above 2,500 meters (8,000 feet). The snow accumulations range up to 800 cm (320 inches) annually.

The southern and eastern coasts of the Kenai Peninsula have a maritime climate characterized by heavy precipitation falling as snow in the higher altitudes (up to 10 m on the ice fields). The Kenai Mountains create a partial rain shadow for the eastern, particularly northeastern Peninsula (Ager 2001).

Physical and Ecological Setting

The Chugach/Kenai assessment area covers a region that's physical and ecological characteristics reflect incredible geological/physical disturbance. Tectonic forces, glacial scouring, and the influence of annual snow produce a legacy of disturbance that results in region-wide patterns of directional change in topography and ecology. Episodic mega-earthquakes along with broad scale subsidence result in periodic resetting of plant succession and re-arranging of plant communities, while the steady progression of the region from almost complete glacial cover to the current interglacial condition results in the steady colonization of exposed land by plants and animals and the migration of biota through the region still occurring today. In this section we provide a brief introduction to the directional patterns of ecological change experienced in the region over the past ten or more millennia – a changing ecological canvas informs us of the potential consequences of human-induced climate change.

As described by Plafker et al. (1992), mega-earthquakes resulting from the sudden shifting of the Pacific and North American plates every 400 to 1,300 years result in instantaneous changes in shoreline of up to 11.3 m (35 ft.). The lateral and vertical shift in the earth's crust simultaneously eliminates and creates conditions for saltwater marsh landscapes and intertidal zones, while drowning forest communities. The consequences of large quakes are clear in environmental legacies -- terraces along shorelines of islands such as Middleton and Montague and forests of dead trees in coastal areas of the Kenai/Chugach assessment area. The periodic nature of large quakes and associated subsidence results in cyclic patterns of vegetation succession along coastal areas. In contrast, retreat of glaciers since their maximum extent 10,000 to 14,000 years ago has led to strong directional (rather than cyclic) changes in geomorphology, hydrology, and ecology.

At the last glacial maximum, the vast majority of our assessment area was under ice. Nunataks appear to have occurred on Knight, Montague, and Hinchinbrook islands resulting in isolated terrestrial refugia in

Prince William Sound (Heusser 1983). These sites would not have supported trees and likely few shrub species persisted. The western Kenai Peninsula, in the snow-shadow of the Kenai Mountains, appears to have maintained several large biological refugia including sites in the northwest Kenai Mountains, the upland between Skilak and Tustumena lakes, and in the Caribou Hills north of Homer (Reger et al. 2007). Other refugia in the Copper River basin and Talkeetna Mountains along with low passes in the Alaska Range provided sources for species to establish in newly exposed terrestrial habitat. Hence, the current vegetation represents the outcome of glacial retreat followed by species re-colonization. Over the last 14,000 years, directional change dominated the assessment area and continues today. These directional processes began earlier on the western Kenai than around the Sound. Earlier deglaciation and substantial refugia (that occurred in a variety of life zones) west of the Kenai Mountains facilitated more rapid plant migration than in the sound. Retreating ice on the Kenai allowed the expansion of birch (*Betula* sp.) and herb tundra beginning 14,200 years ago. Early postglacial vegetation included shrub birch (*Betula nana*), alder (*Alnus*), willow (*Salix*), grasses (*Poaceae*), sage (*Artemisia*), herbs, and ferns. Boreal spruce, likely white spruce (*Picea glauca*) from refugia, along with paper birch (*Betgula papyrifera*) was present 8,500 years ago and began expanding significantly about 5000 ybp on the Kenai (Ager 2001, Ager et al. 2010, Jones et al. 2009). By about 2,900 ybp mountain hemlock (*Tsuga mertensiana*) and Sitka spruce (*Picea sitchensis*) began invading the eastern and northern valleys of the Kenai Mountains.

Deglaciation progressed in Prince William Sound sufficiently to expose low-lying areas by 9000 ybp resulting in colonization by coastal tundra and sedge tundra (Heusser 1983). In many areas, alder established early following deglaciation and persisted for over 1000 years before tundra again dominated in areas such as College Fjord. Conifers first become apparent about 2,700 ybp. Coastal rainforest tree species migrated from southeast Alaska (where they persisted through the Holocene) following the prevailing storm tracks northwestward along the gulf coast and across Prince William Sound. This migration of Sitka spruce, mountain hemlock, cottonwood (*Populus trichocarpa*), yellow cedar (*Chamaecyparis nootkatensis*), and western Hemlock (*Tsuga heterophylla*) appears to have required thousands of years to travel hundreds of kilometers. About 2000 ybp alder pollen declined and western hemlock and associated coastal rainforest species developed forest communities (Heusser 1983; 349).

While the preceding summary of transition from Pleistocene ice-cover to contemporary vegetation is portrayed as a unidirectional conversion, the dynamic nature of the region is further demonstrated by short-term changes also observed in records of environmental history. Periods of glacial advance occurred 3200 and 2500 ybp and again quite recently with the little ice age, resulting in glacial advances and subsequent retreat (Jones et al. 2009). While not as obvious in the glacial record, significant warm periods occurred. Patterns of high temperatures in the Northern Hemisphere during the Medieval Warm Period (about 950 to 1100 ad, fig. 4) appear similar to that of the late 20th century (1961-1990) and the rate of increase was comparable to that of the past couple decades (Mann et al. 2008). Figure 4 illustrates both the variability in global temperatures (note the Medieval Warm Period (~1000 ad) and the little ice age (centered about 1700 ad) over the past 1700 years and the unique nature of the pattern the past couple decades.

Clearly the physical and biological systems of the Kenai/Chugach have experienced radical change in the past, prior to the dramatic climate shifts being explored in this assessment. The vegetation currently occurring in the region is different from the past, and resulted from directional change that began with the exposure of land following the last glacial maximum (fig. 5). This tapestry of change represents critical context for interpreting the scenarios for future dynamics the region may experience as a result of human-induced climate change in the next half century. Strong abiotic drivers – ice, snow (depth and slides), tectonics, and geology -- interacting with climate and the historical legacy of species colonization and the formation of new vegetation communities have resulted in the environment that people use across the Chugach/Kenai region today. This document seeks to explore the character of this environment in the future as a consequence of continued, but accelerated climate change.

Social, Economic, and Cultural Setting

The assessment area is comprised of three relatively distinct regions. The Municipality of Anchorage and the Kenai Peninsula Borough are each organized as single political jurisdictions equivalent to counties, while the Prince William Sound region includes the independent cities of Whittier, Valdez, and Cordova as well as the predominantly Native villages of Tatitlek and Chenega. These communities comprise the Chugach Census Sub-area, a geographic area with no regional government (fig. 6).

Each of the three regions represent distinct social and cultural settings with substantially different demographic and economic characteristics (table 1). Anchorage is home to more than 40% of Alaskans and is the dominant source of demand for recreation and tourism on the Chugach National Forest and on the Kenai Peninsula. The Kenai Peninsula Borough is a rural area with about 60,000 residents, with 4 major population centers - Kenai (pop. 7,100), Homer (pop. 5,003), Soldotna (pop. 4,163), and Seward (pop. 2,693) – supporting most of the population but a significant number of residents dispersed along the limited road system. In contrast, the Chugach Census sub-area has very little private land and fewer than 7,000 residents, most of whom are concentrated in Cordova and Valdez. Cordova, Tatitlek, and Chenega are not connected by road to the rest of the state, but are served by the state-run ferry system known as the Alaska Marine Highway.

The relatively high median household income in the Chugach Census Sub-area (the Prince William Sound region) stems primarily from oil industry employment at the Valdez terminal of the Trans-Alaska Pipeline. Despite this concentration of high-wage private sector jobs, the PWS region is much more dependent on fishing and local government for employment than the other two regions. There is one actively-fished limited entry permit for every ten employed residents in PWS, compared to one per 20 employed in the Kenai Peninsula and three per thousand in Anchorage.

Subsistence is an important component of household consumption and well-being for many people, particularly in the Kenai and Prince William Sound portions of the assessment area. Harvest and use of wild native species represents a significant component of the culture across all three regions but occurs within different social, economic and cultural contexts. Fay et al. (2005) summarized the results of a major subsistence study covering Prince William Sound communities affected by the Exxon Valdez oil spill:

> The study found strong evidence of the continuing importance of subsistence harvests and uses of fish and wildlife resources in the study communities. Virtually every household in each community used subsistence resources and the vast majority engaged in harvest activities and was involved in sharing. Harvest quantities in the 1997/98 study year as estimated in usable pounds were substantial, ranging from 179 pounds per person in Cordova to 577 pounds per person in Chenega Bay. Tatitlek's annual harvest was 406 pounds per person, though in 1988/89 the person annual harvest was 644 pounds. Harvests were also diverse, with the average household using 15 or more different kinds of resources in the study communities. (Fay et al. 2005, p. 73)

Personal use fish harvests – harvests by Alaska residents for personal use and not for sale or barter (Fall et al. 2014) -- are also significant to many households throughout and beyond the study region.[1] In 2012, total personal use salmon harvests in the Chugach-Kenai region were 781,132 fish; 69% of which came from the Kenai River dip net fishery and 18% of which came from the Chitina Subdistrict dip net fishery. (Fall et al. 2014) (table 2). Anchorage and Kenai Borough residents harvested about two-thirds of the total, with an average harvest of 1.4 fish per person. The personal use and subsistence activities connect

[1] From a legal and management perspective, "Personal use" fisheries differ from "Subsistence" fisheries depending on determinations by the Alaska Board of Fish. According to the Alaska Department of Fish and Game, "Subsistence uses of wild resources are defined as 'noncommercial, customary and traditional uses' for a variety of purposes." http://www.adfg.alaska.gov/index.cfm?adfg=fishingsubsistence.main

individuals, families, family groups, and communities to specific landscapes, often resulting in an intimate understanding of natural resources and important connections to place. The annual calendar for many residents is organized around the timing of natural events (e.g. salmon returns) and longstanding traditions associated with the timing, methods, location, processing, and use of native plants and animals.

Tourism and recreation are important to the economies of all three regions (Colt et al. 2002, Crone et al. 2002, Fay et al. 2005).[2] An estimated 500,000 people recreate on the Chugach National Forest (CNF) each year; much of this use occurs in the summer but winter, snow-based recreation is becoming increasingly popular as well (USDA Forest Service 2014). A total of 145 commercial recreation special use permits have been issued for 2016 on the CNF, of which 134 are for outfitting and guiding services (Chugach National Forest, 2015). Recreation on the CNF is supported by a system of facilities, roads, and trails across the eastern Kenai Peninsula, Prince William Sound, and the Copper River Delta region. This infrastructure includes over 100 recreation sites, approximately 520 miles of trails, and just over 90 miles of road. Many facilities are most popular during a specific period of the year, when conditions are best for fishing, hunting, boating, mountain biking, snowmachining, or backcountry skiing, to name a few activities. More information on recreation settings, opportunities, and use levels can be found in the Forest Plan Revision Assessment (USDA Forest Service 2014: Chapter 3).

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[2] Because tourism is not a defined industry for statistical reporting purposes, it is not possible with current data to determine tourism employment or income for specific regions in Alaska.

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Tables

Table 1. Economic and demographic characteristics illustrating significant differences in the social and economic environment across three portions of the assessment area.

	Community Name	Municipality of Anchorage	Kenai Peninsula Borough	Chugach Census sub-area
Population and Housing				
	Population July 1, 2014	300,549	57,212	6,707
	Population July 1, 2011	295,920	56,623	6,733
	avg annual growth 2011-2014	0.5%	0.3%	-0.1%
	Occupied Housing Units in 2010	107,332	22,161	2,676
Employment and Income				
	Residents Employed in 2013	130,673	23,909	3,152
	Private Sector (%)	85%	80%	74%
	Local Govt. (%)	8%	14%	20%
	State Govt. (%)	7%	6%	6%
	Median Household Income	77,454	61,793	91,338
Fishing and subsistencee				
	# of limited entry permit holders who fished	388	1,097	334
	Estimated ex-vessel value of fish harvested	46,630,382	136,807,046	62,137,013
	Federal rural subsistence priority?	No	Yes	Yes except Valdez

Table 2. Salmon harvest from Chugach-Kenai region personal use fisheries, 2012.

	Sockeye salmon	Other salmon	Total salmon
Lower Cook Inlet	137	1,757	1,894
Upper Cook Inlet			
Kenai River dip net	526,992	8,243	535,235
Kasilof River dip net	73,419	2,229	75,648
Other Upper CI	29,195	695	29,890
Subtotal, Upper Cook Inlet	629,606	11,167	640,773
Total Cook Inlet	629,743	12,924	642,667
Chitina Subdistrict dip net	136,441	2,024	138,465
Total Chugach-Kenai region	766,184	14,948	781,132

Figures

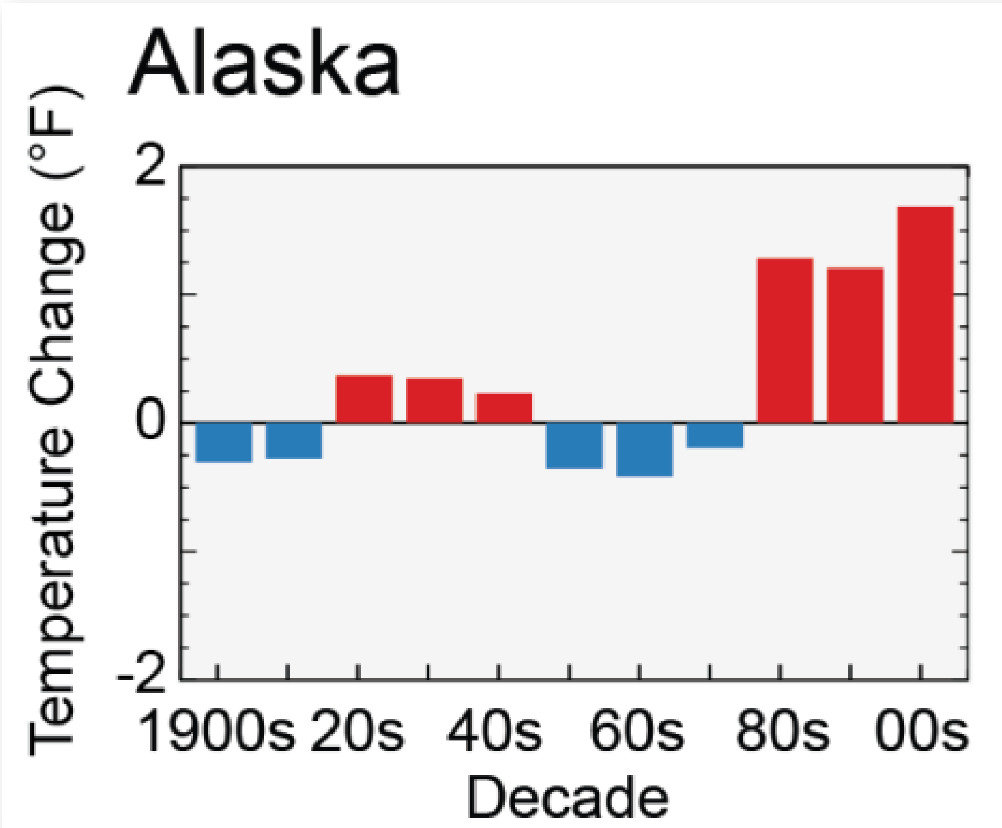

Figure 1. Bars show Alaska average air temperature change by decade for 1901-2012 relative to the 1901-1960 averages. The far right bar (2000s decade) includes 2011 and 2012. (Figure data source: Melillo et al. 2014, NOAA NCDC / CISC-NC).

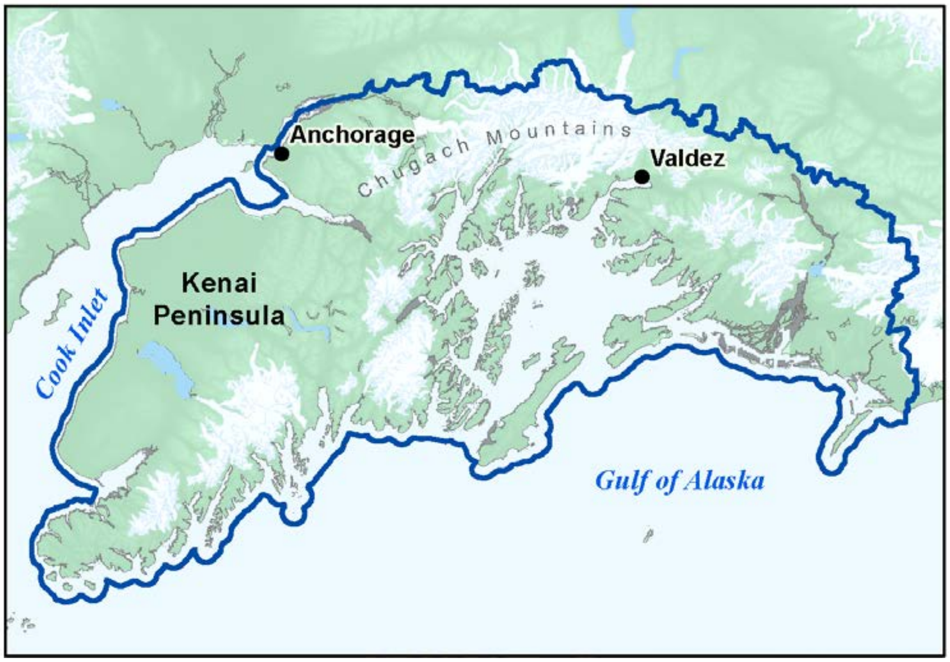

Figure 2. The Chugach National Forest and Kenai Peninsula Assessment Area within southcentral Alaska.

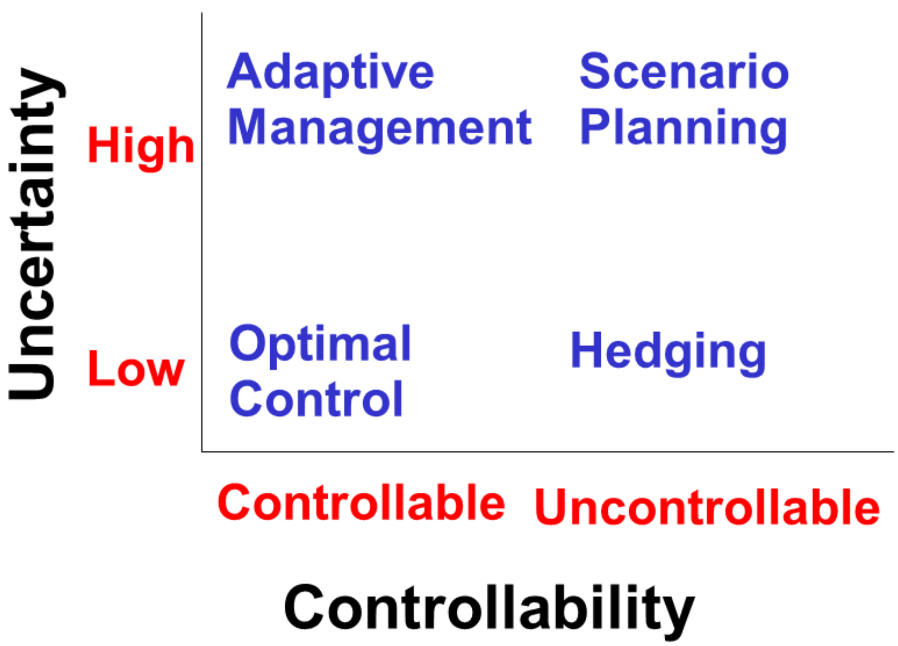

Figure 3. Alternative approaches to management (Peterson et al. 2003; 365).

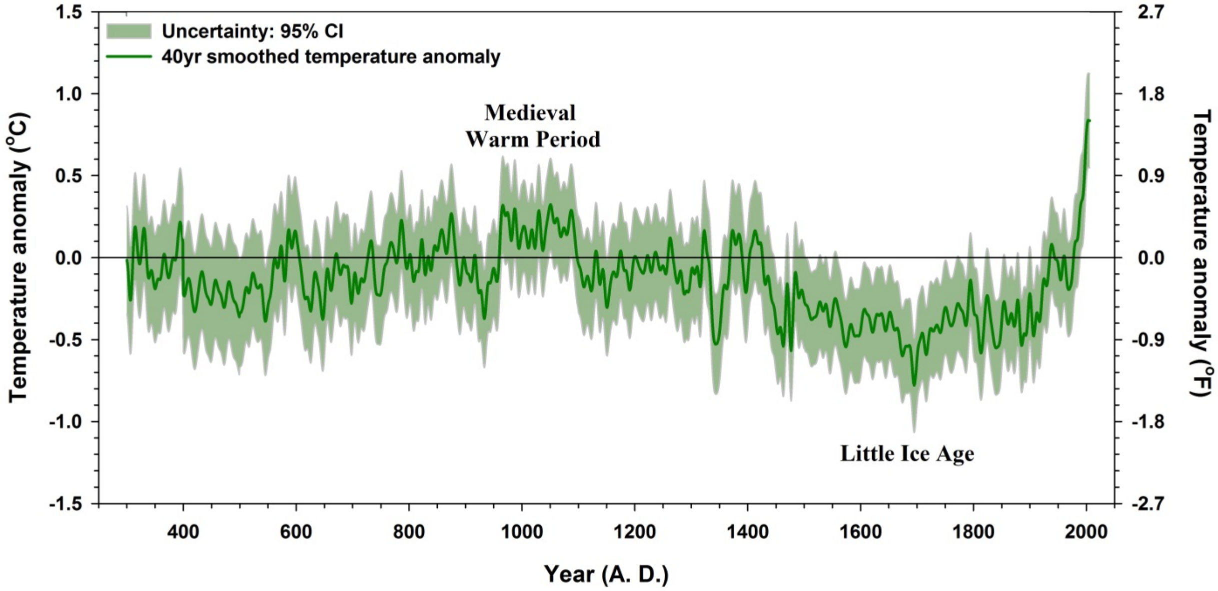

Figure 4. Pattern of surface air temperatures for the northern Hemisphere over the past 1700 years (based on data published in Mann et al. 2008).

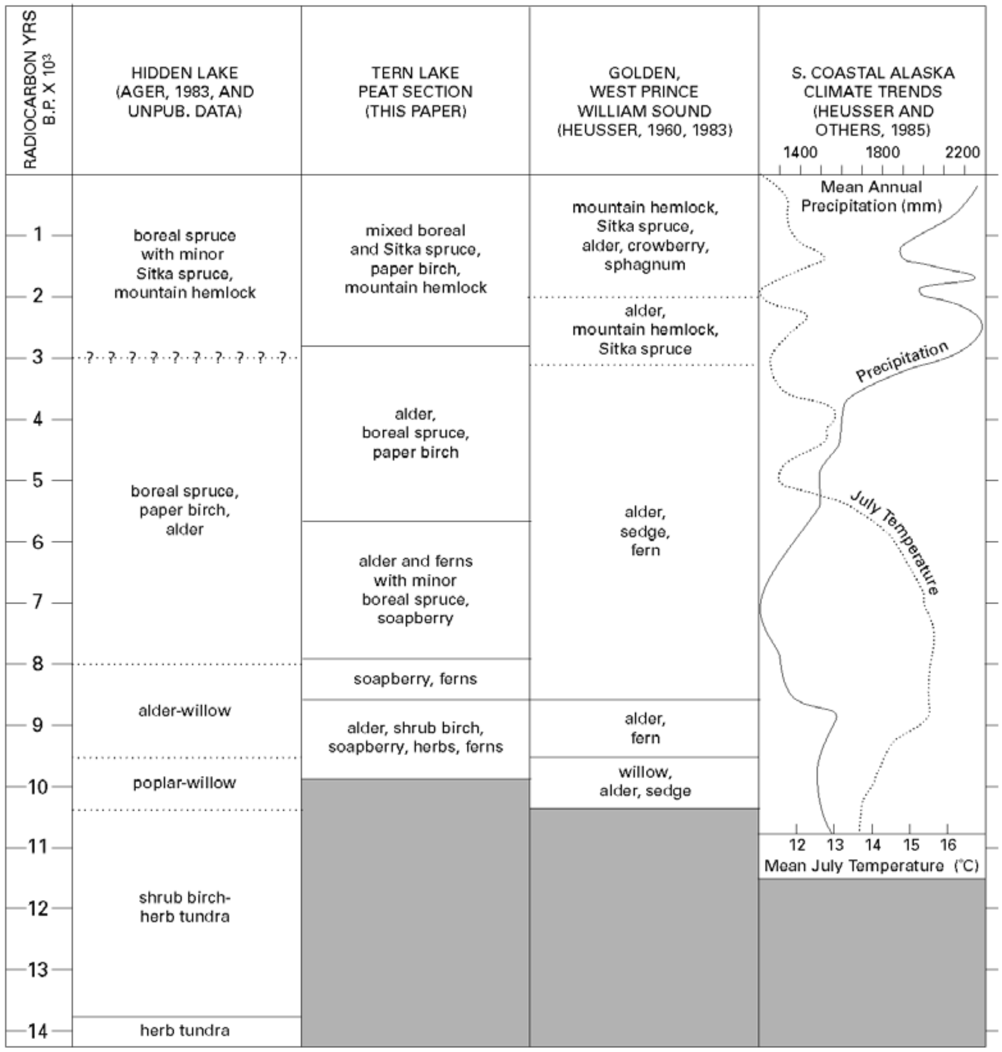

Figure 5. Illustration of postglacial vegetation histories from three sites located in different climatic regimes across the northern Kenai Peninsula and northwest Prince William Sound: (1) Hidden Lake, in the partial precipitation shadow of the Kenai Mountains, (2) Tern Lake peat section, north-central Kenai Mountains, near the boundary between transitional and maritime climate types, and (3) Golden, a peat section from a coastal maritime climate. Holocene climate trends for the southern coast of Alaska (modified from Heusser et al. 1985 as cited by Ager 2001) show the coincidence between relatively warm, dry climate and the spread of boreal-forest plants during the early Holocene and cool, wet climate and the development of coastal forest vegetation along the coast of Prince William Sound and the eastern Kenai Peninsula during the late Holocene (From Ager 2001).

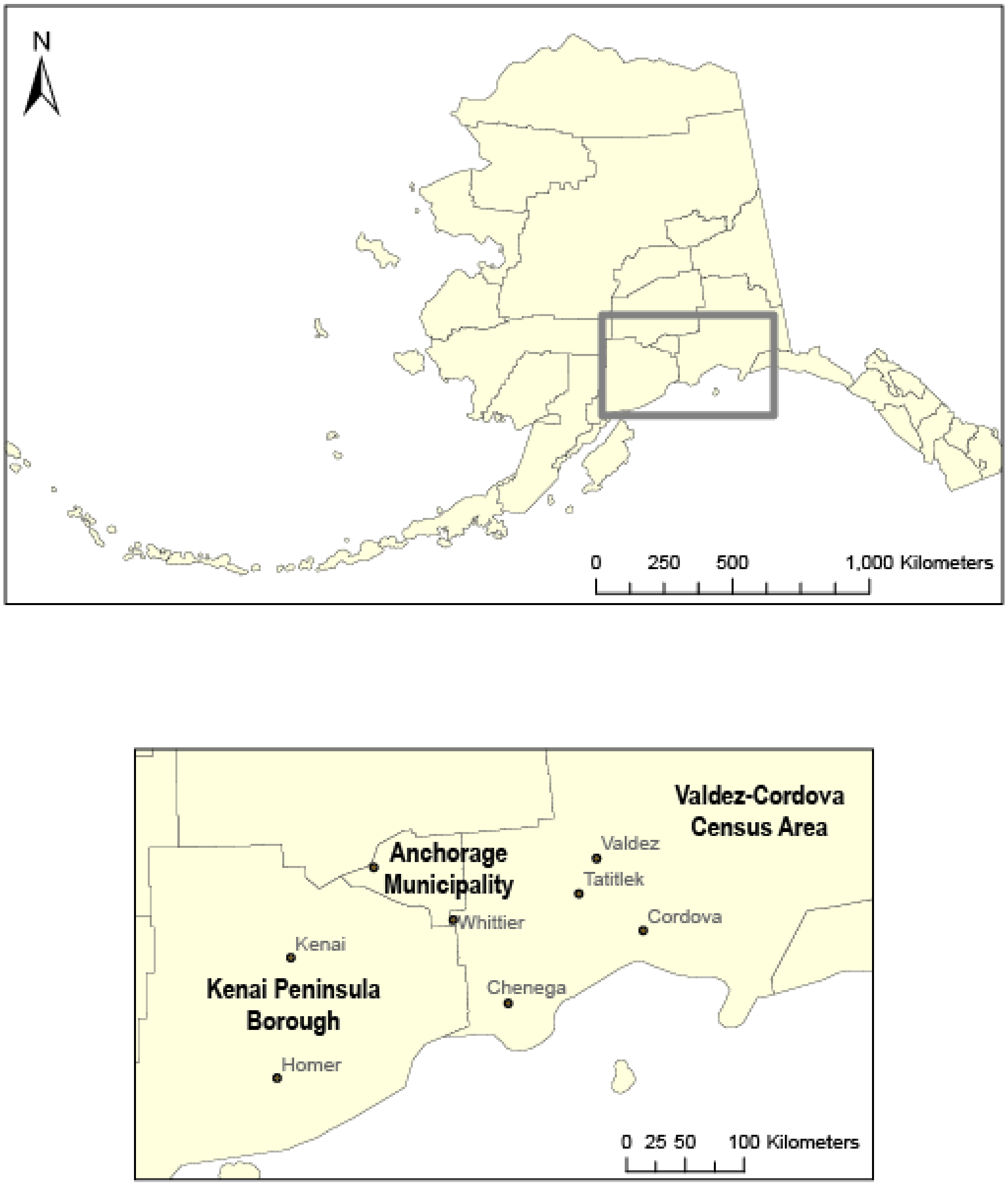

Figure 6. Administrative setting of the assessment area illustrating the context of the Kenai Peninsula Borough, Municipality of Anchorage, and Chugach Census Subarea in Alaska, 2013.

Chapter 2: CLIMATE CHANGE SCENARIOS

Nancy Fresco[1] and Angelica Floyd[1]

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Summary

- Downscaled climate projections developed by Scenarios Network for Alaska and Arctic Planning (SNAP) are useful for examining potential changes in a range of climate variables, and have been used to develop quantitative and qualitative stories regarding climates that may be experienced across the assessment area in the future.
- In this section, we examine basic SNAP projections, including mean and extreme monthly temperature and precipitation for July and January; the timing of thaw and freeze; and the expected monthly proportions of snow versus rain ("snow day fraction").
- Overall, the assessment area is expected to become warmer in the middle of this century, with earlier springs, later autumn, a longer growing season, and shorter less severe winters.
- Some increases in precipitation are likely, but overall snowfall will decrease, due to higher temperatures, particularly in the late autumn (October to November) and at lower elevations. The snowline will move higher in elevation and further from the coast. This change in snow dominance will also be explored in other chapters.
- [see later comment regarding outcomes of changing climate]

Introduction

Alaska climate has undergone rapid changes. Substantial warming has occurred at high northern latitudes over the last half-century. Most climate models predict that high latitudes will experience a much larger rise in temperature than the rest of the globe over the coming century however, the geographic location of the assessment area, in a coastal region with complex weather patterns and tortured topography results in patterns of change dissimilar to arctic Alaska (SNAP 2015). To understand the impacts of climate change in the Chugach/Kenai region, these changes must be examined in the context of the dynamic nature of the region.

Development of Climate Scenarios

Much of the climate modeling for this project uses datasets downscaled and/or derived by the Scenarios Network for Alaska and Arctic Planning (SNAP: www/snap.uaf.edu), a program within the University of Alaska. SNAP is a collaborative network that includes the University of Alaska, state, federal, and local agencies, NGO's, and industry partners. SNAP provides access to scenarios of future conditions in Alaska and other Arctic regions for planning by communities, industry, and land managers. For this effort we chose a set of models that perform particularly well in southcentral Alaska. For additional detail, including discussion of model uncertainty, see Appendix A and www.snap.uaf.edu

SNAP climate projections are based on downscaled outputs from five General Circulation Models (GCMs) that were selected, based on regional accuracy, from the fifteen GCMs used by the

Intergovernmental Panel on Climate Change (IPCC) when preparing its Fourth Assessment Report released in 2007 (IPCC 2007, Walsh et al. 2008). SNAP scaled down these coarse GCM outputs to 771m resolution, using baseline climatology grids (1971-2000) from PRISM (Parameter-elevation Regressions on Independent Slopes Model). This effort employed CMIP3 models because those were the most recent available at the onset of the project. These results focus on the A2 greenhouse gas emissions scenario as defined by the IPCC. Although the IPCC's most recent report, the Fifth Assessment Report (AR5)(IPCC 2013), refers to four Representative Concentration Pathways (RCPs) rather than the scenarios described in the Special Report on Emissions Scenarios (SRES) published in 2000, the slightly older model outputs used in this analysis are still relevant within the new framework (Fussel 2009). The A2 scenario outputs fall between those of RCP 6 (a mid-range pathway in which emissions peak around 2080, then decline) and RCP 8.5, the most extreme pathway, in which emissions continue to rise throughout the 21st century (Rogelj et al. 2012). For the purposes of comparison, some results from the slightly more optimistic A1B scenario are also shown in Appendix A.

Temperature and precipitation values are expressed as monthly means for decadal time periods (current, 2020s, 2040s, and 2060s). This averaging helps smooth the data and reduce the effects of model uncertainty such that a clear trend emerges, facilitating comparison among decades. However, some uncertainty does occur across broader timeframes, due in part to the influence of the Pacific Decadal Oscillation (PDO) and other long-term, broad-scale climate patterns (Bieniek et al. 2014, Walsh et al. 2011). Uncertainty is discussed further in Appendix A.

January and July data were selected in order to highlight changes in the most extreme months of winter and summer. Changes in shoulder season characteristics and timing are also biologically and culturally important, and are captured via assessment of freeze and thaw dates.

Changes in Temperature

Modeled data for the current decade show that temperatures in the coldest month of the year (January) range from a mean decadal average of approximately -20°C (-4°F)in the mountains to slightly above freezing along the coastline south of Cordova and Valdez. In the hottest month, July, the mean decadal average temperatures (15°C, or 60°F) are found in low-lying inland areas, while the coolest temperatures are again found at the mountain peaks, where averages are well below freezing (-7°C, or 19°F).

These temperature profiles are expected to change over time, with all areas warming by about 3°C (5°F) in the next fifty years. Areas with July temperatures below freezing are unlikely to undergo significant glacial melting, although it should be noted that daily highs will exceed mean values, and that direct solar radiation can drive effective temperatures above recorded air temperature.

Winter temperature change is expected to be even more extreme (fig. 1). Average temperatures in the coldest month of the year are predicted to rise from only slightly above freezing in the warmest coastal areas to well above freezing, or approximately 4.5°C (40°F). Moreover, these warm temperatures will spread inland toward Cordova, Valdez, and Seward, with above-freezing Januaries dominating across all coastal regions of the Chugach, and some areas as much as twenty miles inland. Many rivers shift from a below-freezing to above-freezing temperature regime. Across the region, winter warming is expected to be approximately 3°C to 3.5° (4.5-6°F). While the greatest impact of summer warming may be in the coldest regions of the Chugach, where snow and glaciers will be most influenced, the greatest winter impacts may be in the warmest coastal and near-coastal regions, where a shift is underway between winters with seasonal mean temperatures below freezing to winters in which the mean temperature across December, January, and February is above freezing. Although this shift does not preclude significant frost and snowfall, it does imply a change in the duration and prevalence of snowpack and ice.

Areas with mean January temperatures above freezing may still experience days or even weeks of freezing temperatures, and daily lows are likely to be significantly cooler than mean values. However, it is unlikely that significant ice formation would occur in such areas, particularly given the fact that sea water freezes at approximately -2°C (28°F) rather than at 0°C (32°F). For brackish water, intermediate freezing temperatures are the norm.

Changes in Precipitation

The projected decadal trend is toward greater precipitation in both January and July. However, model predictions for precipitation are less robust than those for temperature, in part because precipitation is intrinsically more geographically variable. In addition, while, precipitation is predicted to increase, inferring the hydrologic status of soils, rivers, or wetlands based on this greater influx of water is problematic. Increases in temperature (and associated evapotranspiration) may more than offset increases in precipitation, yielding a drying effect. Changes in seasonality and water storage capacity can also affect the hydrologic balance. Furthermore, a shift in the percentage of precipitation falling as snow can drastically alter the annual hydrologic profile.

While current SNAP models do not directly address storm frequency, the literature suggests climate-change-driven increases may be occurring in the frequency and severity of storm events in the Gulf of Alaska and Bering Sea (Graham and Diaz 2001, Terenzi et al. 2014).

Model Results: Freeze, Thaw, and Warm Season Length

SNAP interpolates monthly temperature and precipitation projections to estimate the dates at which the freezing point will be crossed in the spring and in the fall. The intervening time period is defined as “summer season length”. It should be noted that these dates do not necessarily correspond with other commonly used measures of “thaw”, “freeze-up” and “summer season.” Some lag time is to be expected between mean temperatures and ice conditions on lakes or in soils. Different plant species begin their seasonal growth or leaf-out at different temperatures. However, analyzing projected changes in these measures over time can serve as a useful proxy for other season-length metrics.

Across the assessment region, date of thaw in the spring is expected to come earlier. Large areas of coastal and near-coastal land are projected to shift from early spring thaw to the “Rarely Freezes” category. This is likely to correspond with lack of winter snowpack and an altered hydrologic cycle. Primarily frozen areas –are expected to shrink significantly. Elsewhere, changes are projected to occur as a shift of 3-10 days, on average. For example, the A2 scenario shows spring thaw occurring in Soldotna and Kenai around April 4 in the current decade, but in late March by the 2060s.

Autumnal changes are, overall, projected to be slightly greater than those seen in the spring, with the date at which the running mean temperature crosses the freezing point shifting noticeably later in just a single decade. Major changes in warm season length include incursion of the “Rarely Freezes” zone as far as 20 miles inland; an increase from about 200 days to about 230 days for Palmer, Anchorage, Wasilla, and Kenai; and an even more drastic increase for Seward, Valdez, and Cordova.

Future Snow Response to Climate Change

SNAP data, based on downscaled GCM outputs, do not directly model snowfall as a separate quantity from overall precipitation, measured as rainfall equivalent. However, for the purposes of this project, SNAP researchers used algorithms derived by Legates and Bogart (2009) to estimate snowline and create contour maps depicting the probability of snow versus rain during winter months. The implications of this modeling -- as well as other applications of SNAP data to snow and ice conditions -- are explored in other chapters. However, a summary of snow day fraction outputs is provided here.

A rapid change in snowline is expected over time. This change is illustrated in figure 2 through the change in geographic location where an estimated 90% of winter precipitation will fall as snow (fig. 2). While inter-year variability in snowline is expected to be high in the next ten to twenty years, the modeled snowline shifts well inland from Valdez. By 2040, many areas are predicted to receive less than 30% of winter precipitation as snow, and by the 2060s snowline (as defined by the 90% contour) is predicted to shift to the highest peaks.

In order to assess the snowline during the coldest season, as opposed to the winter as a whole, we also examined the projected snowline for the month of January alone. Results show that for many areas that typically experience almost all January precipitation as snow, this pattern may shift in coming decades. By the 2060s, Anchorage, Kenai, Soldotna, Wasilla, and Palmer may have only intermittent snow cover, even in the coldest month of the year.

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Figures

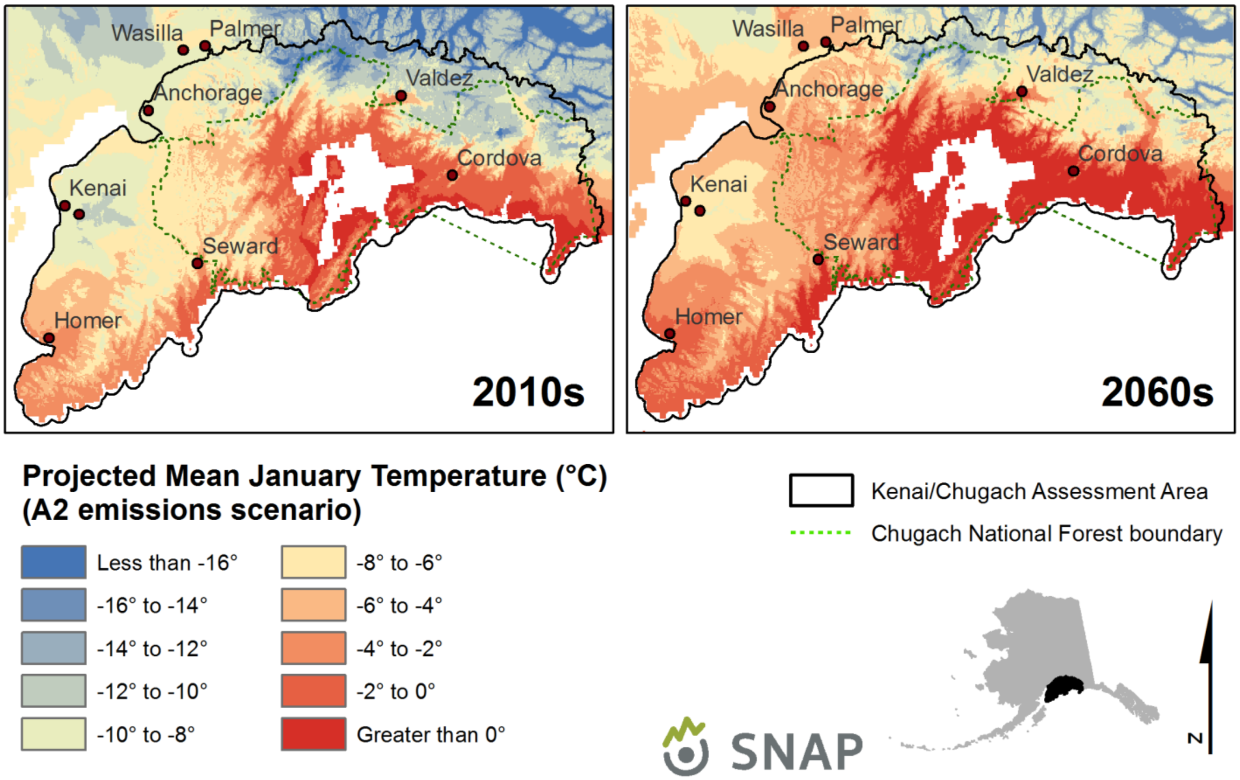

Figure 1. January temperatures for the 2010s, 2020s, 2040s, and 2060s, for the A2 emissions scenario.

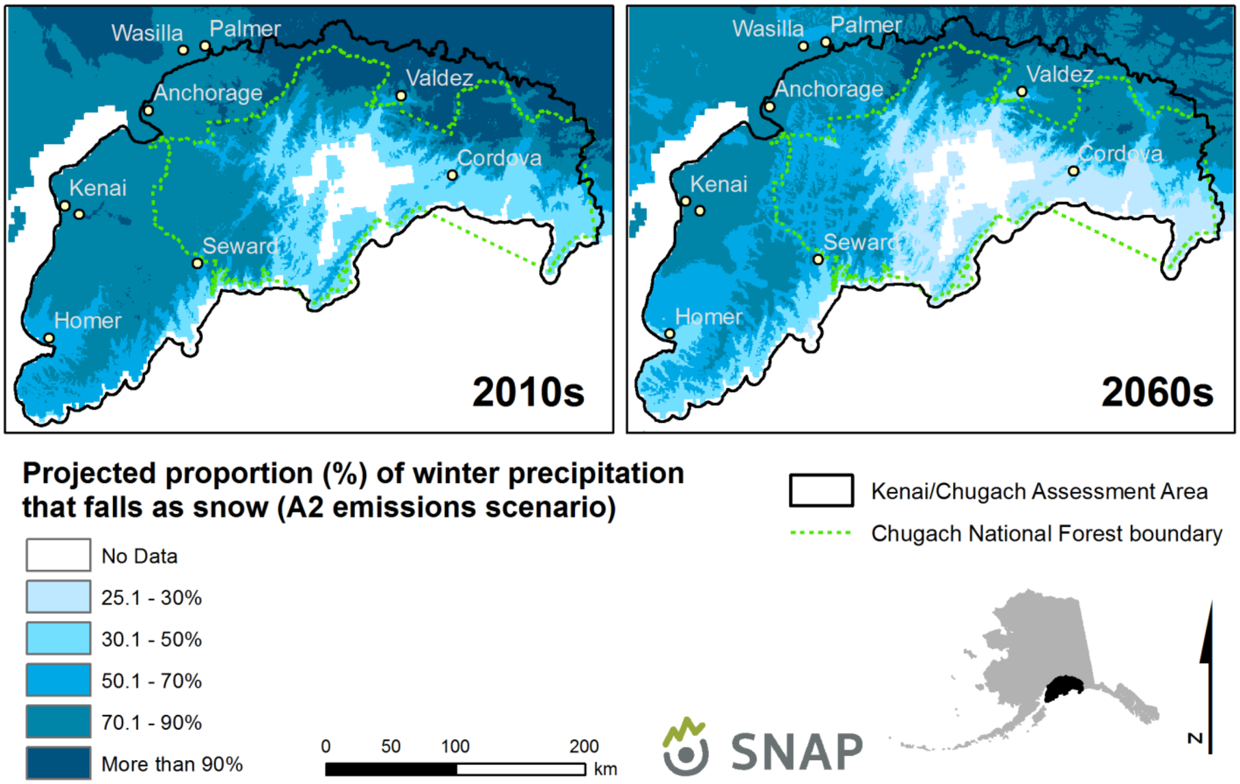

Figure 2. Projected snowline for the A2 emissions scenario for the current decade and a fifty year outlook.

Chapter 3: SNOW AND ICE

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Summary

- Temperature and precipitation are key determinants of snowpack. Therefore climate change is likely to affect the role of snow and ice in the landscapes and hydrology of the Chugach National Forest region.
- Downscaled climate projections developed by Scenarios Network for Alaska and Arctic Planning (SNAP) are useful for examining projected changes in snow at relatively fine resolution using a variable called "snow-day fraction", the percent of days with precipitation falling as snow.
- We summarized SNAP monthly snow-day fraction from 5 different global climate models for the Chugach National Forest region by 500m elevation bands and compared historical (1971-2000) and future (2030-2059) snow-day fraction. We found:
    - Snow-day fraction and snow water equivalent (SWE) are projected to decline most in the late autumn (October to November) and at lower elevations.
    - Snow-day fraction is projected to decrease 23% (averaged across five climate models) from October to March, between sea level and 500m. Between sea level and 1000m, the snow-day fraction is projected to decrease by 17% between October and March.
    - SWE is projected to decrease most in the autumn (October and November) and at lower elevations (less than 1500m), an average of -26% for the 2030-2059 period compared to 1971-2000. Averaged across the cool season and the entire domain, SWE is projected to decrease at elevations below 1000m due to increased temperature, but increase at higher elevations due to increased precipitation.
    - Compared to 1971-2000, the percentage of the landscape that is snow dominant in 2030-2059 is projected to decrease and the percentage where rain and snow are co-dominant (transient hydrology) is projected to increase from 27% to 37%. Most of this change is at lower elevations.
- CNF glaciers are currently losing about 6 km^3 of ice per year, half of this loss comes from Columbia glacier (Berthier et al. 2010).

- Over the past decade almost all glaciers surveyed within the CNF are losing mass (one exception), including glaciers that have advancing termini (Larsen et al. 2015)
- Glaciers not calving into the ocean are typically thinning 3 m/yr at their termini (Larsen et al. 2015).
- In the future, glaciers not calving into the ocean will retreat and shrink at rates equivalent or higher to current rates of ice loss (Larsen et al. 2015).
- Columbia glacier will likely retreat another 15 km and break into multiple tributaries over the next 20 years before stabilizing.
- Other tidewater glaciers have uncertain futures, but will likely not advance significantly in the coming decades.
- These impacts will likely affect recreation and tourism through changes in reliable snowpack and access to recreation and viewsheds.

Introduction

Climate change can be expected to affect where, when, and how much snow and ice occur on the terrestrial landscape. Changes in temperature and precipitation alter the fundamental physical processes that govern the buildup and melt of snowpacks, the growth or decline of glaciers, and the timing and quantity of important hydrologic processes such as streamflow. However, the impact of climate change on snow and ice depends on what time frame is considered, how local weather and climate respond to hemispheric or global changes in temperature and precipitation, and, at finer scales, how these changes play out over the complex and rugged topography of the region. Some of these changes are intuitive, but the complex interaction between topography, elevation, and broad scale weather patterns may lead to some unexpected dynamics for both snow and glaciers.

In this chapter, we discuss the mechanisms by which climate affects snow and ice in the Chugach National Forest and surrounding region. We also synthesize available scientific literature and data to characterize plausible impacts of climate change on snow and ice in the future.

Climate change and its effects on snow and ice

Climate – the statistics of weather over time (usually 30 years or more) – is determined by the combination of temperature, precipitation, wind, the nature of storms, atmospheric pressure, and other factors characteristic of a place. Climate also includes the interannual to decadal (and longer) variability in those characteristics and the regional to global mechanisms that cause it. However, what is “characteristic” is changing rapidly in ways that are explainable only by global climate change, that is, those trends in climate that are significantly influenced by anthropogenic greenhouse gas emissions. Projecting possible climate impacts on snow and ice processes requires understanding the mechanisms by which weather and climate affect snowpack and glaciers.

Snowpack

In places where snow and ice were historically common, changes in climate can be expected to affect snowpack development, distribution and melt as temperature increases and the timing and quantity of precipitation change. Increasing temperature impacts snowpack directly by affecting both the seasonal timing of snowmelt and the period of the year that is cool enough to promote snowpack accumulation. First, as temperature during the fall, winter, and spring increases, there is increased likelihood that storms will coincide with above-freezing temperatures, and the proportion of precipitation that falls as rain instead of snow increases. Second, as spring temperatures increase, the timing of spring melt is pushed earlier in the year. In places where storms historically occurred at temperatures near freezing, a small increase in temperature can result in relatively large decreases in snowfall as the form of precipitation changes to rain. In contrast, in places where storms historically occurred at temperatures well below freezing, the impact is proportionally less. Rain-on-snow events may also increase with temperature, but are difficult to predict and model. Furthermore, despite increased temperature, increased precipitation may result in substantial increases in snow at high elevations where precipitation was less abundant in the past but future temperatures are rarely expected to be above freezing. Therefore, at colder locations where temperature is consistently below freezing (usually at higher elevations), increased future precipitation could result in increased snowpack.

Glaciers

Glaciers are the result of a climate that consistently produces more snowfall during winter than can be melted in summer. The surplus of snow accumulates over decades to millennia and eventually compacts into ice. As the ice deepens, the glacier's immense weight causes the ice to flow downhill until the ice reaches lower elevations, which are warmer and receive less snowfall, thus allowing the excess ice to glacier melt. A glacier can maintain a constant size and shape if the net gain of snow in the upper accumulation zone of the glacier perfectly offsets the net amount of ice lost in the lower ablation zone (melt zone). If the amount of melt exceeds the amount of snow accumulation, the mass budget of the glacier becomes negative and the glacier will shrink, adding that water to streamflow, and eventually, the oceans. The size of glaciers is thus inextricably linked to the relative amounts of snowfall and melt -- two terms that are expected to change with a changing climate.

Glacierized basins (i.e., ice covered currently as opposed to glaciated, or historically ice covered) produce 2–10 times more runoff than similarly sized, non-glacierized basins (Mayo 1984). When compared to ice-free basins, basins with only a few percent of basin ice coverage exhibit notable differences in streamflow at all time scales. Given two identical neighboring basins, with the sole exception being 20% ice cover in one basin, cumulative annual streamflow will be higher in the glacierized basin, and the annual streamflow will have a longer period of higher flow, due to continued release of water after basin snow cover is melted. Daily streamflow will exhibit diurnal variations, even in the absence of snow, due to melt. Historically, higher glacial coverage in a watershed translates to increased runoff rates, later timing of peak streamflow in late summer, and decreased inter-annual variability (Fountain and Tangborn, 1985, Jansson et al. 2003, O'Neel et al. 2015). Meanwhile water clarity, stream temperature and streambed stability all decrease (Fleming 2005, Hood and Berner 2009, Milner and Petts 1994).

Glaciers in the Chugach National Forest region (CNF) receive an exceptional amount of snow each winter (estimated at greater than 3000mm water equivalent precipitation averaged over the region) and are also subjected to exceptional amounts of melt in summer. They must flow exceptionally fast to offset the high mass turnover and therefore are relatively quick to respond to climate variability and change.

Tidewater glaciers – those that calve icebergs into the ocean – are controlled not only by climate; they are also sensitive to the changing ocean temperatures and fjord shape. These controls are powerful enough to affect a glacier's mass balance by controlling additional ice loss through iceberg calving. Subtle changes—perhaps in climate and/or glacier shape—can cause the glacier to accelerate, which causes more iceberg calving, more acceleration and hence a feedback loop that causes the glacier to lose far more ice than climate would allow alone – referred to as a 'rapid' retreat (e.g., Meier and Post 1987). On the other hand, a similar-sized change in climate may yield no response at a different stage of the tidewater glacier advance-retreat cycle (Post et al. 2011). Columbia Glacier in the CNF is an archetypal example of this process; it has lost 155 km^3 of ice in the past three decades but less than 10% of this loss has been due to climate (Post et al. 2011, O'Neel 2012, Rasmussen et al. 2011). In concept, rapid retreats continue to impact glacier mass balance after a retreat from deep ocean water. The retracted geometry (removal of ablation area) favors positive mass balance, and mass gains are likely even in a climate unsupportive of widespread mass gain/advance for land-terminating glaciers (Post et al. 2011). Calving dynamics are the reason for the wide range of tidewater glacier behaviors currently occurring in Prince William Sound and will be responsible for complex future pattern of glacier change in the CNF (Larsen et al. 2015). Glaciers in the CNF that do not terminate in the ocean are not subject to these interactions and as such, when reviewing current and projecting future changes in CNF glaciers, it is important to distinguish between tidewater glaciers and all others (Arendt et al. 2002, Larsen et al. 2015). How climate and tidewater dynamics are affecting glaciers now and how they may affect glaciers in the future will be discussed in following sections.

Impacts of climate change effects on snow and ice

Streamflow timing and volume

Collectively, the expected changes in snow and ice will have impacts on the hydrology of systems both within and downstream from mountains and glaciers (O'Neel et al. 2015). These hydrologic changes can in turn have significant impacts on – and be influenced by - terrestrial, riparian, and coastal ecosystems. Geology and geography, along with the physical and ecological changes in watersheds, affect the response of hydrography to climate change, so responses can vary significantly from watershed to watershed within a region. There are also strong ice-ocean-ecosystem linkages and feedbacks including nutrient delivery, primary productivity, which likely have implications for fish, marine mammal, and bird populations. This illustrates the importance of an interdisciplinary approach and modeling to understand climate change impacts in complex systems.

Neal et al. (2010) and Hill et al. (2015) estimated that 43% (370 km^3/yr of 870 km^3 /yr) of the runoff running into the Gulf of Alaska is from glaciers in Southeast Alaska and is comparable in volume to the Mississippi River despite being 7 times smaller. Freshwater delivery to the ocean affects ocean circulation, sea level change (Larsen et al. 2007), and possibly also hydropower resources. For example, the Alaska coastal current, which flows north from the Gulf of Alaska, delivers more fresh water via marine supply than is supplied to the Arctic Ocean by any two large rivers (Weingartner et al. 2005.) Climate warming eventually influences the net mass balance of land-terminating glaciers and thus the seasonal timing and amount of streamflow in streams dependent on them (Jansson et al. 2003), but the glacier volume buffers the streamflow response – there is a smooth increase with glacier melt, then decrease in response to declining volume. Runoff increases until glacier contribution decreases, and then runoff decreases. In much of Alaska, the current status of such river systems is unknown because the relative position of the watershed in the evolution of glacier melt and hydrologic delivery (runoff) is unclear. Changes in runoff depend on complex seasonal evolution that is itself a function of details of glacier structure (firn, piping, water saturation and ponds and channels, and bedrock geometry). These factors affect downstream flows via their influences on the diurnal timing and within-season variability in streamflow. A study of monthly flow for nine rivers in Canada (Fleming 2005) indicates that non-glacial basins have a freshet peak with comparatively long persistence into summer. As little as 2% ice cover in basin is enough to transfer a hydrograph to glacial basin dynamics. Glacierized basins have a much larger freshet relative to baseflow, and higher flows persist longer. In Alaska, comparison of a continental glacier (Gulkana) with a coastal, land-terminating glacier (Wolverine) suggests a coastal glacier has comparatively high fall flow, and larger peaks the rest of time (O'Neel et al. 2014). Projecting future stream flow in glacierized basins is difficult. Precipitation amount and timing, temperature, and local topography and glacier morphology all affect dynamics of glaciers and thus the streamflow. But glacier shape changes are difficult to predict (Jost et al. 2012). Cumulative mass balance at Gulkana glacier steadily decreased, (-25m area-average thickness since 1960s), while Wolverine glacier had an increase rate of mass balance gain in the 1980s, but a rapid decrease since then, so mass losses have been proportionally less on the coast (-16m; O'Neel et al. 2014). Coastal glaciers have fared better historically due to different seasonal climate (more precipitation and less summer heat), but the slope of the decrease in mass balance is similar over the last 20yrs. Coastal glaciers are probably more vulnerable over the long-term because they have a temperature regime closer to 0°C than those in the interior

Role of glaciers in oceanography, marine ecosystems

Glacier mass balance and effects on streamflow are not the only expected impacts of climate change associated with glaciers. For example, the surfaces of glaciers have been shown to support microbial ecosystems. Atmospheric deposition of nutrients, the resulting primary and heterotrophic production at the glacier surface, microbial activity underneath the glacier ice (Skidmore et al. 2000), and hillslope runoff combine to result in large material contributions to the marine environment. Heterotrophic carbon in glacier runoff (Hood et al. 2009) is nearly that of some boreal forest runoff (glacial DOC = 12–18 kg/C/ha/yr, boreal forest DOC export 22–86 kg/C/ha/yr). The runoff flux from glaciers to streams or ocean is therefore large, and is bioavailable including nutrients (phosphorous), micronutrients (iron), and contaminants (mercury and others). However, much as with glacier changes, the flux response is locally variable –biochemistry and turbidity vary widely in streams dominated by glacial runoff (Hood and Berner 2009). Riverine biodiversity increases with basin glacierization (Jacobsen et al. 2012). Despite this variability, it is important to recognize the substantial input of organic nutrients from glaciers; a characteristic that was only recognized recently (Hood et al. 2009).

Glacier runoff also affects near-shore ecology in part because of the input of nutrients including organic matter to the system. Euphausiids and zooplankton can thrive in glacier-dominated fjords (Arimitsu et al. 2012), as do coastally adapted birds (Mehlum and Gabrielsen 1993). Diving seabirds forage on upwelled crustaceans and thus have high fidelity to glacial habitat. Glaciers provide refuge from predation for seals and glacial born pups have short weaning times (Blundell et al. 2011, Herreman et al. 2009, Womble et al. 2010). The effects of glacial turbidity on light affect vertical migration of fish. In clear water, sunlight penetrates >100m, moonlight penetrates <50m, but in sediment-laden water sunlight penetrates less than 50m. As a consequence, mesopelagic fishes are nearer the surface during daylight hours. Consequently, forage fish plausibly spend more daylight hours at the surface and are therefore possibly more available to birds.

For fjord glaciers, warming and melting result in changes to coastal (baroclinic) current through changes in physical oceanography. These result in effects for the whole circulation pattern in the fjord, which changes rate of iceberg production, forage fish survival and productivity, and the timing and structure of currents. Beyond their influence on individual fjords, glaciers play an important role in delivering freshwater to the Gulf of Alaska. Where tidewater (calving) glaciers have a direct connection to the ocean environment, there is a direct interaction, through melting of ice below sea level, referred to as submarine melt. Submarine melt has been shown to be capable of melting the majority of ice delivered to the calving front from upstream during summer months. In the CNF region, the ocean is warm enough to melt ice 5 or 6 months a year, and freshwater contribution to the marine environment peaks in autumn. In such environments, there are enormous amounts of sub-marine melt as all tidewater glaciers are grounded below sea level in the ocean (Bartholomaus et al. 2013, Motyka et al. 2013).

Future Snow Response to Climate Change

Strengths and limitations of climate modeling for snow impacts

One tool available for assessing the plausible impacts of climate change on snow and ice is future climate modeling. Global climate models (GCMs) take advantage of modern computing capacity to simulate historical and future climate from “first principles” – knowledge of the physical properties and behavior of the atmosphere, ocean, land surface, and other factors as well as how they interact to affect climate. It is worth noting that the climate modeling community has recently transitioned from the CMIP3 group of climate models used in the fourth IPCC assessment (AR4) to the next generation, or CMIP5 group of models, which generally have finer resolution and (slightly) more advanced treatment of the climate system. Knutti and Sedlacek (2013) concluded that CMIP3 and CMIP5 can be considered realizations of the same probability spectrum of plausible climate scenarios, and at the time of this writing, CMIP5 downscaled climate output for Alaska did not exist. Given the mid-century focus of this assessment, the scenarios presented in this chapter should be broadly consistent with CMIP5 models with the higher RCP emissions scenarios (4.5. 6.0, or 8.5) because those do not diverge appreciably from A2 until the 2050s or 2060s. Despite modern computing capability, however, the atmospheric resolution of GCM simulations is commonly performed at about 0.5 – 1.0 degrees latitude (roughly 35 to 70 miles), though some models exceed this resolution. This limits the local processes that can be resolved by the model. For example, rugged topography such as in the Chugach National Forest might result in 3000m elevation differences at the scale of one or two cells in a climate model.

To make climate model output more applicable to finer landscape features, a process called "downscaling" can be used (See Chapter 2). The many approaches to downscaling vary in complexity. Whether increasing complexity is advantageous or not depends on the question. For example, understanding future monthly or seasonal changes in temperature and precipitation averaged across several climate models may not require the same detail as understanding daily responses in climatic extremes, which may require complex statistical relationships between historical gridded data and GCM cells. In Alaska, the Scenarios Network for Alaska and Arctic Planning (SNAP) uses an approach called the "delta" method to relate gridded historical climate information (PRISM) to the expected CHANGE for each GCM. That is, the difference between the GCM historical climate and the GCM future climate is calculated, and that change (or "delta") is added to (for temperature) or multiplied by (for precipitation) the historical value.

The delta method, while less complex than some other approaches, has a straightforward and easy to understand method for dealing with climate model bias. The bias in a climate model is the degree to which it is too warm or cold (wet or dry) compared to measured climate in the historical record. For example, mountain ranges that are too small to be resolved in the model create real rain shadows that the model cannot "see", resulting in too much modeled precipitation in the rainshadow and not enough in the mountains. Bias correction uses historical data to estimate the correction of such model error. The delta method does not explicitly model the error – instead it takes the simulated historical climate and the simulated future climate from the GCM and uses the difference between the two to estimate the change expected by the model in the future. This is an indirect control of bias, but it is straightforward and effective, and does not result in substantial loss of information for monthly or seasonal questions.

SNAP's future projections come from five different GCMs (CCCMA-CGCM3.1 t47, GFDL-CM2.1, MPI-ECHAM5, MIROC3.2 medres, and UKMOHadCM3) that have been evaluated for their fidelity to Alaskan climate (a "reanalysis", i.e., not directly from station data, Walsh et al. 2008) during the instrumental period (1958-2000). Deltas for each of these GCMs have been computed and applied to gridded, interpolated historical climate (PRISM) at 30arc second (similar to 800m resolution, about 771m at 60 degrees North latitude). This results in more localized (downscaled) estimates of historical and future temperature and precipitation. However, the consequences of changes in precipitation and temperature for snowpack at a location as fine as 800m are complex. Snowpack is affected by other factors that are not commonly downscaled to such fine resolution, and without this information, climate models cannot simulate snowpack at local scales. For example, the difference in snow accumulation on one 800m pixel compared to a neighboring pixel is a product of elevation, orientation to prevailing winds, wind effects on redistribution, vegetation and the variations in storm track from year to year. Elevation and aspect are fixed – they do not change appreciably over the time frame important for such questions. However, year-to-year differences in wind redistribution of snow and storm tracks can affect the two neighboring pixels differently. It is also critical to remember that the *changes* in temperature and precipitation at the two pixels are effectively the same, though their individual values may be different due to the downscaling. Downscaled climate output gives us the ability to examine those changes, but there is considerable local information that climate models do not "see" – they do not resolve the wind differences and topography for the two example pixels. Therefore "forecasts" of 800m snowpack for a given year or even a given decade are beyond the scope of such work. However, the changes from historical snowpack to future snowpack over the duration of the "climatology" (30 year period) average out the factors that result in large year-to-year and pixel-to-pixel differences and focus instead on the trends to be expected given changes in temperature and precipitation.

In the following analyses, we have chosen to focus on the midterm impacts of climate change (SRES Scenario A2) over a thirty-year period in the future – 2030-2059. This is a long enough time span that the averages of temperature and precipitation ("climatology") are comparatively robust to interannual and decadal variation in climate, but sufficiently close in the future that it has bearing on management time horizons considered between now and the 2030s. For this initial analysis, we have chosen to analyze impacts for 500 m (~1650 ft) elevation bands, which avoids confounding the results too much with local differences. The changes in the projections below should therefore be considered "averages" with some variability to be expected within the elevation bands and the thirty-year period due to topographic and interannual variability in factors that affect snowpack.

We focus on three aspects of how snow may change in the future: snow day fraction, snow water equivalent, and snowpack vulnerability. Snow day fraction addresses the changes that could reasonably be expected in the proportion of precipitation that falls as rain versus snow now and in the future. Snow water equivalent addresses the consequences of changes in both precipitation and snow day fraction for snow accumulation on the land surface during the cool season. Finally, snowpack vulnerability addresses the proportion of precipitation entrained in the snowpack during the cool season.

Projected effects of climate change on snow-day fraction in Chugach National Forest

McAfee et al. (2013) developed models of decadal snow-day fraction for all of Alaska at 800m[1]. Snow-day fraction is the ratio of days with precipitation falling as snow to the total number of precipitation days. For example, a snow-day fraction of 30% means that of the days with measurable precipitation, on 30% of those days the precipitation fell primarily as snow. A projected change of -20% snow day fraction would result in a future value of 10% snow-day fraction, but would represent a decrease of 67% of the historical value.

Here, we present a summary of snow-day fraction for Chugach National Forest based on data and projections developed by McAfee et al. (2013). They developed decadal historical data (1900 – 1909, 1910 – 1919, etc. to 2009) and future projections (2010 – 2019, 2020-2029, etc. to 2099) for different future greenhouse gas emissions scenarios (B1, A1B and A2 SRES emissions scenarios, e.g., Nakicenovic et al. 2000). Given the 2030-2059 projected future timeline for this assessment, we chose to use the future climates derived from scenario A2, which result in similar temperature changes as A1B until about the middle of the 21st century, after which they result in more warming than A1B. Recent emissions are comparable to the trajectory of both A1B and A2 scenarios, so we elected not to consider B1 scenarios. We used an historical benchmark climatology of 1971-2000, and thus averaged the three decadal 800m resolution downscaled estimates of snow-day fraction for the 1970s, 1980s, and 1990s. We did the same for the downscaled projected values for the 2030s, 2040s, and 2050s. We subtracted the historical data from the future projections to estimate the change in snow-day fraction. All analyses to this point were done for the whole state of Alaska.

Using the project domain for the Chugach National Forest Vulnerability Assessment and the digital elevation model associated with the SNAP products, we developed eight 500m elevation bands for analysis, from sea level (0m) to >3000m (fig. 1, table 1). We calculated the mean historical (1971 – 2000) and projected future (2030 – 2059) % snow-day fraction for the elevation bands (i.e., over all pixels in each elevation band).

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[1]Data: http://www.snap.uaf.edu/data.php#dataset=historical_monthly_snow_day_fraction_771m

User's Guide: http://www.snap.uaf.edu/files/data/snow_day_fraction/snow_fraction_data_users_guide.pdf

Snow-day fraction changes by elevation band

The results of this analysis are summarized in table 1 and figure 2. In the text that follows, the comparisons described are between the historical snow-day fraction and the five-model mean future snow-day fraction. Individual model projections may be more or less than the 5 model average (see fig. 2). When the range of model projections includes the historical mean, it is less clear that the projected changes are distinguishable from the historical variability. In no case is the 5 model future mean greater than the historical mean; in a few cases, notably in May below 2000m and July at elevations above 2000m, the GCM with the highest future snow-day fraction exceeds the historical mean.

In most months at all elevations, the five-model mean indicates projected decreases in snow-day fraction. These decreases are most pronounced at lower and mid elevations (2000m and less) in the late autumn / early winter (October, November and December). For elevation bands 2000m and below, the projected (2030-2059) model with the highest snow day fraction is less than the historical (1971-2000) means for these months. Decreases in these elevations vary with month (fig. 3) and elevation (fig. 2), but are higher in October (mean -13%, model range -6% to -24%) and November (mean -12%, model range -4% to -25%) than in December (mean -4%, range -2% to -8%). Differences in October are evident at elevation bands above 2000m, but the projected changes decrease as elevation increases (fig. 2). For elevation bands 1500m and below, there also appears to be a decline in February snow-day fraction (around -13% average, model range -36% to -2%), although February has one of the largest ranges of projected future responses of any month, particularly at 2500m and below (fig. 2).

The difference between historical and future snow-day fraction as well as the disagreement among climate models initially decreases with increasing elevation. However, models agree more on warm season (April to September) changes below 2000m than they do on cool season (October to March) changes. At elevations above 2500m, models agree more on cool season changes than they do on warm season changes.

Projected effects of climate change on snow water equivalent in southcentral Alaska

Snow water equivalent (SWE) is the amount of water entrained in a given volume of snowpack. Snowpacks with identical depth but different densities have different water content. SWE is a way of putting snow depths and densities, which vary considerably, on consistent hydrologic footing.

Using the same scenarios as for snow day fraction, we used historical and future gridded precipitation[2] to estimate the precipitation totals and projected changes for the key cool season months October to March. Snowpack obviously can accumulate in southcentral Alaska, particularly at the highest elevations, earlier in the autumn and later in spring than these months, but this is a comparatively standard hydrologic season comprising the bulk of the snowiest months. For each month, we multiplied the snow day fraction by the precipitation to estimate the total maximum SWE. Local processes, such as wind redistribution, sublimation from the surface or tree canopies, and melt could well affect the actual SWE, so these should be interpreted as estimates of the climatically determined component of SWE.

Snow water equivalent (SWE) changes projected using this methodology indicate different responses at different elevations (fig. 4) across the cool season and substantial differences across months (table 2). Averaged across the cool season, SWE would be projected to decline most in the autumn (October and November) and at lower elevations (less than 1500m), an average of -26% for the 2030-2059 period compared to 1971-2000, with the largest decreases at lower elevations and in October. In contrast, from December to March at elevations above 1000m, the 5 GCM average SWE is projected to increase an average of 12%, with the largest increases at highest elevations in January and February. At less than

[2] Data: http://www.snap.uaf.edu/data.php#dataset=historical_derived_precipitation_771m

500m, SWE is projected to decrease in all months except January and March, which have models projected increases (table 2). For the cool season as a whole, the 5 model GCM average projects decreases in SWE at elevations less than 1000m and increases above 1500m (fig. 5, table 3). Agreement across GCM models is reasonably good at the lowest and highest elevations – most of the models agree on decreases in monthly SWE for Oct.-Mar. at the lowest elevations (<1000m) and increases at the highest elevations (>2500m). However, at mid elevations, some models project decreases and some increases (table 3, fig. 6).

Projected effects of climate change on snowpack vulnerability in southcentral Alaska

SWE projections used in conjunction with precipitation projections allow calculation of an index of snowpack vulnerability (indicated by changing exposure to melt) to climate change (see Elsner et al. 2010 and Mantua et al. 2010 for details). This index is the ratio of April 1 SWE to the total precipitation between October 1 and March 31. Values less than 0.1 (that is, 10% of the precipitation was entrained in snowpack on April 1) indicate a "rain dominant" hydrology. Values between 0.1 and 0.4 indicate a "transient" hydrology, where the annual hydrologic cycle is partially driven by rain and partially by snowpack. Values greater than 0.4 indicate a "snow dominant" hydrology, where snowmelt strongly affects the timing of peak flow.

We used two separate data sets to evaluate snowpack vulnerability. First, UW CIG (University of Washington Climate Impacts Group 2012) developed historical (1950-2000) and future (2030-2059) temperature and precipitation output from the same five GCMs as Walsh et al. (2008) downscaled to 0.5 degree (~35mi or 65km) over a domain of the entire North Pacific and used them as input to the Variable Infiltration Capacity model (VIC, e.g., Liang et al. 1994) to estimate SWE. However, they developed these for the SRES A1B emissions scenario, which arguably results in slightly less warming by the middle of the 21st century than scenario A2 used for the SNAP data above. Although the 0.5° products are ultimately too coarse to allow small (e.g., 12-digit HUC) watershed calculation and comparison, these projections can give a regional perspective on snowpack vulnerability using independent methods.

Second, we calculated the same snowpack vulnerability index for areas within the Chugach Vulnerability Assessment using the calculations for SWE in the previous section in conjunction with SNAP's precipitation projections to calculate snowpack vulnerability index for the same gridded surfaces in the snow fraction and SWE analyses above, allowing smaller watershed comparisons.

In both cases, we calculated the snow vulnerability index (April 1 snow water equivalent / October to March total precipitation) for a 2030-2059 time period. Compared to historical, the results from the UW CIG (2012) data averaged across all 5 future models for the Chugach vulnerability assessment domain suggest a decrease in the percentage of the landscape that is snow dominant and an increase from 8% to 13% transient (63% increase) and increase from 0% to 3% rain dominant (table 4).

Figure 7 shows the historical and projected future distribution of the index for each climate model using the SNAP data and the SWE calculated here. According to the finer downscaling approach SNAP used, the historical condition of the HUC 12 watersheds Chugach Vulnerability Assessment domain was about 73% snow dominated (>40% of October to March precipitation entrained in snowpack) and 27% transient (between 10% and 40%) by area, with no rain dominated watersheds. The 5 model average future distribution is projected to be about 63% snow dominated and 37% transient, still with no rain dominated watersheds (table 5). The five GCMs vary considerably in their future proportion of the landscape in transient versus snow-dominated watersheds (fig. 7, table 5), with a lower estimate of snow dominant watersheds at 55% (CCCMA-CGCM3.1 t47) and a higher estimate at 67% (UKMOHadCM3).

Of the 551 HUCs in the domain, 4% (23) shift from snow dominated to transient, while none shift from transient to rain dominated or from transient to snow dominated. Among historically transient HUCs, the average change in snowpack vulnerability index is about -0.04, but among the historically snow-dominated HUCs the average change is 0.00. This value, however, is misleading - the comparatively large increases (+0.4 - +0.8) in the historically most snow dominated HUCs (at higher elevations and with SVI > 0.55, see fig. 8) cancel out the changes in other snow-dominated HUCs. For example, in figure 8, lower elevation HUCs become closer to rain-dominant, but below about 1200m, a large number of HUCs becomes a class away from becoming transient.

Limitations: caveats and uncertainty

There are several important limitations on the future snow-day fraction, SWE, and snow vulnerability index projections. First and foremost, stations with long, complete, and well- documented historical climate observations are sparse in Alaska, especially above 500m in elevation. The equations developed by McAfee et al. (2013) to estimate snow-day fraction from temperature data and the hydrologic modeling done by UW CIG (2012) were constructed almost exclusively from observations below 500m because this is the only information available. In addition the historical observations underlying them are sparser than a comparable area in more populated parts of North America. For example, for snow day fraction, this translates to less certainty in the relationship between observed temperature and the probability of snow at higher elevations, particularly under conditions near freezing (0°C). Given that these higher elevations are areas with less projected absolute change in this analysis and are historically colder, however, this limitation probably does not affect interpretation of the results very much. If anything, the projections are likely to be conservative because the actual lapse rate in coastal areas is likely to be, at least annually averaged, shallower than the gridded climatology assumed environmental average lapse rate of 6.5 °C. Given the topography of the region and the lack of station data applicable to understanding the interactions between topography and storms, the spatial variability of the projections is also undetermined. The aggregation of the pixel values to watersheds and over multiple decades is a partial hedge on this uncertainty.

Second, near-term decadal-to-interdecadal climate variability is not well predicted, even though the climate models of the AR4 generation often simulate realistic variability at those time scales. In fact, decadal prediction is cutting edge science in the most recent generation of climate models and is an active area of research. But it is likely that the temperature trends projected for a future decade could be above or below the future observations due to natural climate variability. We have used a 30-year climatology in both analyses that should, given current knowledge, be relatively robust to such variations. In addition, the fact that the projection window (2030-2059) is before uncertainty regarding future emissions begins to exceed that of models or variability increases our confidence in these projections.

Third, the elevation bands used for the analyses are relatively broad. Under average environmental conditions, the temperature difference across 500m of elevation is often around 3.3°C and sometimes considerably more in drier climates or in some seasons. These elevation bands are used as averages across the study domain, and conditions at a location within an elevation band could be quite different from the average depending on local factors associated with topography, sea ice, etc. and broad-scale factors such as the pixel or HUC's position east or west of Prince William Sound.

Finally, this analysis is not based on an exhaustive approach to future climate scenarios – these are plausible scenarios based on global climate models that have reasonable skill in simulating historical observed climate in Alaska at relatively broad scales. The process of downscaling them provides more physically tailored responses, but it does not resolve some local features and processes that are known to be important in the development and melting of snowpack. The strength of the projections is therefore at coarser spatial scales – watershed to regional, rather than pixel-by-pixel.

For these reasons, the projections presented here should not be viewed as predictions, but rather scenarios of the best available projected future conditions given current knowledge, capability, and resources.

Current and Future Ice and Glacier Response to Climate Change

Since 1950, Alaska has warmed 2°C in winter and 1°C in summer (Arendt et al. 2009). While decadal climate variability explains some of this, increase in temperature is certain, occurring throughout Alaska's weather station network, and is expected to continue with climate change (Stewart et al. 2013). Increases in temperatures have likely led to increased melt but have also led to higher elevation freezing levels and hence conversion of precipitation from what would historically have been snow to rain. Precipitation overall (rain and snow) is expected to increase slightly in the future, though it is not clear if this is happening currently. Only 17% of meteorological stations show an increase in precipitation, all others show no change (Arendt et al. 2009).

These changes in climate have contributed to a widespread loss of ice from glaciers throughout Alaska. Statewide, Alaska glaciers are losing 65 km^3 of ice per year on average, meaning glaciers are losing far more mass to melt than they are able to gain though snowfall (Arendt et al. 2013, Larsen et al. 2015). This volume of ice lost annually is equivalent to more than a year of discharge on the Copper River. The rate of mass loss from year to year is not steady however, variations in summertime temperatures have led to annual losses of up to125 km^3 in 2004 and even a mass gain of 15 km^3 in 2008 (Arendt et al. 2013).

Chugach National Forest (CNF) glaciers are currently losing about 6 km^3 of ice per year, which is equivalent to melting a uniform 60 cm of ice across all glaciers in the CNF (Berthier et al. 2010). However, these changes are not uniform (fig. 9). All non-calving glaciers within the CNF are losing mass. Most of these glaciers are also retreating, and typically thinning at glacier termini by about 3 m/yr (fig. 9, Larsen et al. 2015). These changes are consequence of a warming summer temperatures (Larsen et al. 2015).

Changes in tidewater terminus positions are more complex. Since the 1950s, ten glaciers have retreated more than 0.5 km, only Harvard has advanced more than 0.5 km, and the rest have showed relatively little change (McNabb and Hock 2014). The length and pace of these retreats far outweighs the advances. In the last decade, Harvard, Yale, and McCarty have gradually advanced despite losing mass overall (McNabb et al. 2014, Larsen et al. 2015). Most other glaciers have recently stabilized at retreated positions (McNabb and Hock 2014) but some fully retreated tidewater glaciers have continued to retreat up onto bedrock (therefore ceasing to function as a tidewater glacier) while others have begun a re-advance. Since most of these retreated glaciers still appear to be losing mass, it is more likely that these glaciers will remain close to their stabilized positions or retreat in the near future (warming climate) and less likely that these glaciers would re-advance.

Since Columbia is responsible for half of the CNF glacier ice loss, its future evolution must be considered separately. The volume of Columbia Glacier has declined by approximately 50% in the past 35 years, in one of the largest scale calving retreats ever observed. Future iceberg calving is likely to remain significantly lower than peak levels (O'Neel et al. 2013) due to the large-scale reduction in ice thickness across the entire glacier. The glacier is bedded below sea level 15 km or more upstream of the current terminus, and best projections suggest approximately 20 years of continued retreat (Pfeffer et al. 2015).

O'Neel et al. (2014) analyzed mass balance and streamflow data from Gulkana and Wolverine glaciers to show that both are losing mass as a result of stronger summer ablation. In the continental climate (Gulkana Glacier), positive streamflow anomalies arise primarily from negative annual mass balance anomalies. In the more complex maritime climate (Wolverine Glacier), streamflow has multiple drivers, including melt, and highly variable rainfall and snow accumulation. Although it is common to assume that discharge varies proportionally to annual mass balance for heavily glacierized basins, our data show in maritime climates discharge is less coupled to annual mass balance than the delivery of mass balance to outlet streams as summer streamflow.

Case Study: Monitoring the Retreat of Exit Glacier

Deborah Kurtz, National Park Service

Kenai Fjords National Park

Glaciers are sensitive indicators of climate change. As temperatures warm and/or precipitation decreases, a threshold can be reached where glacial ice is lost faster than it is replenished. This results in a reduction of the ice mass; the surface elevation decreases as ice thins and the area diminishes as the ice margins melt or calve off. This is most easily observed in the change of terminus position where the retreat of a glacier results in an overall decrease in the glacier's length. During the Little Ice Age, a period of cool climate conditions in the Northern Hemisphere, there was widespread advancing of glaciers with many glaciers reaching their most recent maximum extent between 1550 and 1850. Since then most glaciers have been retreating. General trends in past retreat rates can be reconstructed through physical and biological clues in the landscape and analysis of historical photos. Past terminus positions can be determined based on recessional moraines, landscape features that were deposited during temporary periods of a relatively stationary terminus position during an overall period of glacial retreat.

Researchers have used a combination of techniques to document the retreat and changes in the geometry of Exit Glacier at Kenai Fjords National Park (fig. 10). Past terminus positions evident from recessional moraines were identified by Ahlstrand (1983), Wiles (1992), and Cusick (2001) using a combination of field techniques, photogrammetry, tree core analysis and radiocarbon dating. These recessional moraines date back to Exit Glacier's 1815 Little Ice Age maximum position. A series of aerial photography and satellite imagery beginning in 1950 provide additional documentation of the glacier's position. Until the mid-1900s, Exit Glacier extended beyond the restrictive valley walls through which it flows and spread out into the relatively flat and unconfined valley floor. This type of glacier is referred to as a piedmont glacier. From photo documentation we know that Exit Glacier's shape changed dramatically from 1950 when it was still a piedmont glacier to 1974 when the narrower, more constrained shape that we see today was first documented.

In 1980 Kenai Fjords National Park was established and park staff began direct observation of changes to the terminus. Photographic evidence reveals that, from 1983 to 1993, Exit Glacier advanced and the glacier lengthened 75 m (246 ft.) (Tetreau 2005). A recessional moraine resulting from the decade-long advance is visible on the outwash plain today. The glacier began retreating again in 1995. In 2006, park staff began documenting annual terminus positions with a global positioning system (GPS) and calculating annual rates of retreat. These data documented a recent shift in seasonal glacier movement as well. Although there was net annual retreat for these years, Exit Glacier advanced slightly during the winters 2005-2006 through 2008-2009. Beginning in winter 2009-2010, Exit Glacier has been retreating year-round.

Exit Glacier's overall trend of retreat is consistent with the retreat of glaciers around the world. Changes to glacier lengths, documented at Exit Glacier by the change in terminus position, appear in response to past climate conditions and mass balance changes with a response time on the order of decades. However, climate is not the only factor influencing terminus positions. Geometry, basal topography, slope, aspect, and microclimates also contribute to changes. The intermittent advance that was documented at Exit Glacier in the 1980s and 1990s is not unusual amongst glaciers.

Case Study: Evaluating Glacier Change Using Remote Historical and Current Remote Sensing Tools

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Landscape photographs taken by early explorers and historical aerial photography provide records to evaluate multi-decade to century long change in the surface area of individual glaciers. However, evaluating change in glacial cover for an entire region such as south-central Alaska over this same historical period represents a significant challenge. I explored existing maps, aerial photography, and GIS tools to examine changes in surface area occupied by glaciers across the assessment area. After thorough evaluation, I found existing information precluded estimating change with reasonable certainty at this broad spatial extent. Here I document my investigation to assist further investigation of glacier change.

The Randolph Glacier Inventory, (Pfeffer et al. 2014) RGI Version 3.0 released April 7, 2013, represents a reliable source for estimating the current extent of glaciers in the assessment area (http://www.glims.org/RGI/). This GIS product is a global inventory of glacier outlines, supplemental to the Global Land Ice Measurements from Space initiative (GLIMS). Glacier outlines were developed using satellite imagery. Uncertainty is estimated about plus/minus 5% based on comparisons with alternative inventories. To estimate glacier expansion or decline, I sought a source, or combination of source data to map historical glacier extent for comparison with the Randolph Glacier Inventory. I examined:

- Chugach N.F. timber type mapping which includes cover of ice-fields and snowfields (source data - 1:15,840 aerial photography dated from the 1950's – 1970's)
- Chugach N.F. Geology GIS layer: source data 1:250,000 paper map, prepared by the USGS Branch of Alaska Geology, 1985.
- Chugach N.F. Landsystems GIS layer: source data 1:63,360 USGS 15-minute quad maps, 1975, 1978, 1982, and 1983.

These three sources were rejected due to the limited extent of mapping within the assessment area. I also evaluated the National Hydrography Dataset (NHD; http://nhd.usgs.gov/) a digital vector dataset containing water features, including glaciers, maintained by the US Geological Survey (USGS) for the National Map program. For Alaska the source data was mapped at 1:63,360 scale. Source date for the NHD depends on the production date of the initial line work and whether this line work was updated when Digital Line Graph files were created by USGS. Therefore the vintage of the line work for Alaska vary from the 1950's to the present. Examination of the USGS topographic base maps used to form the NHD layer in the November 2012 product suggest they result from aerial photographs taken 1950 and 1957. Upon evaluation, this GIS layer represented the most promising source to compare with the Randolph product[3].

[3] The NHD data was from a data download from USGS NHD in November 2012. The Randolph Glacier Inventory data has since been used to update glacier features in NHD, replacing the previously mapped areas of glacier polygon features in the Waterbody dataset. Any current NHD downloads would no longer allow this type of comparison.

Therefore, I used the National Hydrologic Dataset (November 2012) and Randolph Glacier Inventory (April 2013) to compare the area extent of glaciers and produce a display illustrating areas of potential glacier change (fig. 11). The NHD data were expected to reflect a glacial area extent from an earlier time than the RGI, with a time span assumed to represent 50-60 years.

The Chugach National Forest black and white 1950 and 1959 (1:15,840) aerial photography set and 2008-2009, 4-band orthophotography (60-cm resolution) was used for verification of a sample of watersheds representing the greatest degree of change measured between RGI and NHD.

To examine potential sources of error in the comparison, the map displayed in figure 11 was used to select areas of glacier change to validate with a backdrop of photography. The analysis suggests potential sources of error leading to unreliable estimates of glacier expansion and loss. The most significant source of error displayed as examples in figures 12 and 13 represent errors in mapping glacier boundaries in the NHD. The area of glacial extent is less credible in the NHD than RGI.

In conclusion, using differences in NHD and RGI to detect changes in the extent of glacial boundaries to measure effects of climate change should proceed with caution and careful validation using alternative sources such as aerial photographs. Mapping employed in NHD failed to include some glacial features which were large enough to meet standards for the size of features that should have been captured. In addition, the finer detail of other features was simplified such that the area mapped as glacier was less extensive, leading to potential errors in estimates, particularly of increased glacier cover in NHD/Randolph comparisons. The standard of the NHD feature capture was not consistent across the study area. On the other hand, RGI more frequently misclassified glacial features along rocky ridges and very steep slopes, particularly shadowed slopes, which NHD tended to correctly interpret as rock in the areas where I compared both datasets to photography. My evaluation of NHD and the resulting comparison of NHD with RGI correctly identified the three cases of advancing tidewater glaciers: Harvard and Surprise Glaciers in the College Fiord area and Mears Glacier in north central Prince William Sound. This suggests some value in cautious use of these tools to examine glacier change. Using NHD and RGI to detect recent ice expansion was mainly useful for selecting areas for further examination. I caution against estimating differences in the two datasets for broad measures of increase in glacial extent. In conjunction with validation, local areas can be evaluated.

Comparison of NHD and RGI adequately detect retreat along the margins and valley edges of glaciers. Based on my broad evaluation of glacial extent from NHD and RGI, the greatest loss of ice surface area in the domain of our assessment was associated with Columbia Glacier, Miles and Allen Glacier in the Copper River system, and Bear Glacier in Kenai Fjords (fig. 14).

Snow and Ice: Effects on Ecosystem Services

Introduction and conceptual framework

In this section we consider how the findings discussed above –especially higher elevation average snow lines and fewer average snow days – might affect the ecosystem services related to tourism, recreation, and visitation of the study area.

Our approach is to treat the natural resource interaction with humans in their roles as producers and consumers as a complex social-ecological system (SES). Snow- and ice-dependent tourism and recreation is a subsystem within this SES. So, too, are specific activities such as heli-skiing. This kind of analysis is relatively new. Previous analyses (notably Haufler, Mehl, and Yeats 2010) have considered the implications of climate change on broader ecosystem services. However, as one of the few published papers focusing on the human dynamics of the tourism industry notes:

> While tourism and the environment has been studied extensively …, the concept of resilience as a means to understanding the impact of disturbances or stress on a system has rarely been used….. (Becken 2013)

While that paper uses resilience rather than vulnerability as the organizing concept, the general point about such analyses being relatively new still applies.

It is challenging to isolate the effects of climate change on the SES and relevant subsystems because they are affected by numerous other stocks, stresses, and forces of change. As Becken (2013) puts it:

> The emphasis on present and future **climatic disturbances** allows for a focused analysis; however, it is important to note that tourist destinations experience a wide range of **other stress factors** simultaneously.” (Becken 2013)(emphases added).

Some of these other stress factors include global and national market forces and prices, changing technology and preferences (e.g., the rise of snow-biking), and key decisions taken by major industry players (cruise lines, Alaska Railroad) and government agencies.

The stability landscape concept (Walker et al. 2004) provides a useful framework for this discussion. Each subsystem is currently within a relatively stable state known as a basin of attraction. Each basin has a single “low point” toward which the subsystem tends absent any disturbance. The *latitude* (L) of the basin is a measure of how much the subsystem can be disturbed before it leaves the basin. For example, summer boating and sea kayaking in Prince William Sound has very wide latitude with respect to warmer temperatures. The *resistance* (R) of the system is a measure of how sensitive it is to perturbation. For example, if snow at high elevations remains dry despite average temperature increasing by 4 degrees C, this would be high resistance. Finally, the *precariousness* (Pr) of the subsystem is a measure of how close it is to a tipping point or threshold. For example, a ski area that has had several mediocre seasons due to economic recession might have very low cash reserves, and thus be precariously close to going out of business due to a bad snow year.

These concepts make more sense when combined into a summary such as this one:

> Social–ecological systems can be close to, or far away from, important thresholds (Pr). They can be easy or hard to change (R). The range of dynamics that can be accommodated while still retaining basically the same system can be large, or small (L). (Walker 2004 p. 7)

The disturbances affecting the stability landscape are also usefully characterized as “slow” vs. “fast” changes (Carpenter and Turner 2000). The Alaska economy and its tourism industry are subject to the “fast” influences of crude oil prices, national or global economic recession, and weather. Climate change operating to raise the snowline over 50 years is a “slow” change, as is an aging and growing resident population. Similarly, humans can respond with “fast” adaptations such as postponing a trip or drawing on financial reserves. But over "slow" time scales regions within Alaska, and Alaska itself, can become significantly less unique and/or less preferred as a destination by both residents and tourists.

Affected Ecosystem services

The snow and ice-related ecosystem services most likely to be affected in ways that influence the recreation and tourism subsystems of the Chugach-Kenai SES are:

- Reliably deep snow
- Reliably dry snow
- Reliably accessible snowpack
- Stable (meaning storm-free) weather

As a general proposition, there is one general threshold of greatest interest; the change from snow to rain or from sub-freezing to above-freezing temperatures.

Deep snow

The dearth of snow during the 2014-15 season demonstrates that the presence or absence of snow has significant economic and social consequences for the people and businesses of the Chugach-Kenai SES. Ski areas were shut down (Edge 2014, 2015) and backcountry skiing was limited or nonexistent (Hollander 2014). Dog races were moved (Alaska Dispatch News 2015).

While it is generally recognized that snowfall is volatile and most businesses can shrug off an occasional bad snowfall, as long-term averages change **or as expectations change**, people may begin to substitute away from snow-dependent activities in specific places. For example, Hatcher Pass, approximately 50 km north of Anchorage, can be thought of as the place where Anchorage skiers may go when all else fails. It is a good example of economic substitution within a range of specific ecosystem services in specific places. It costs more in time and fuel to get there, so only the more ardent skiers go there. However, it may be that Hatcher is the "substitute of last resort" for some people; Even the fear that it may be dry could cause further substitution out of Alaska altogether.

Dry snow

Dry snow is the ecosystem service that supports powder skiing and arguably separates Alaska in the marketplace from Pacific Northwest, and certain other skiing destinations. There is some evidence that heli-skiing is already shifting northward and/or out of the Kenai Peninsula. The Chugach Powder Guides Web site (www.chugachpowderguides.com/trips) lists only the Girdwood/Alyeska and the Seward/Pacific Coast areas as specific skiing zones. While there is currently no direct evidence to support the proposition, it seems reasonable to speculate that as the study area snowpack becomes wetter on average, it will be less desirable as a destination for both Alaska residents and nonresident tourist-visitors.

Reliable access to snowpack

This ecosystem service is a function of the elevation of snowline and whether existing trailheads provide access to snow. People can walk to reach skiable terrain (as they famously do in New Hampshire) but snowmachines cannot travel long distances over dry land and regulations limit snow machine use when snowpack is shallow. The findings above suggest that access to snow could become a concern as the snow line rises. Existing trailheads could become "stranded" below snowpack for snowmachine access. Users would naturally seek out other access points that still connect with snow resulting in potential crowding and other consequences.

An obvious adaptation response is to extend trailhead access to reach higher snowlines. While this may be impractical for existing trailheads, new ones could be planned over a 10-20 year horizon to accommodate an ascending snowline.

Storms and storm-free weather

Storm frequency and intensity could also negatively affect visitation. Tour operators must build potential storm-related interruptions into their planning and revenue projections much like businesses must plan for a certain percentage of bad debts or concert promoters must plan for cancelled shows. Insurance markets could emerge or expand to address these concerns, with the overall effect being an increase in the cost of supplying "good-weather experiences." There could also be a decrease in the demand if customers are forced to bear the risk of cancellation or postponement. The burden of disruptions will be shared by both producers and consumers of recreation and tourism experiences. While exact allocation will depend on market conditions, the overall effect of more storms and extreme weather will likely be to reduce the quantity of tourism excursions and experiences, and to increase the prices paid.

Substitution in the face of change

Within limits, there is substantial scope for substitution of locations and activities within Southcentral Alaska. In this respect, the latitude (L) of the stability landscape is reasonably wide for winter recreation and tourism as a regional or statewide activity and business sector. Backcountry skiers and snowmachiners can migrate north seeking drier or more accessible snow. Snowmachiners, in particular, may simply go higher within existing terrain, assuming they can still gain initial access to the snowpack. Some people will substitute hiking for skiing. However there will be a loss of quality or recreation value; if there were not then these shifts would have already happened. Furthermore, some substitution among recreation opportunities may also be negatively influenced by changing climate. For instance, a shift from skiing to rafting may be limited if changes in precipitation reduces stream flow patterns such that the season of rafting is constrained.

If the quality and cost of recreational opportunities in the Chugach-Kenai region shift in ways that favor other winter recreation areas that are closer to large population centers, then some nonresident tourists are less likely to make the long trip to Alaska and more likely to fly to places like Utah. Similarly, some Alaska residents – referred to by economists as those "at the margin" -- may substitute a backcountry ski trip in British Columbia for a ski trip within the Chugach-Kenai region. While these kinds of substitutions may be relatively rare, each one will have a much larger economic impact than simply shifting recreation locations within South-central Alaska.

Maintaining ecosystem services in the face of climate change

Many of the same measures to stabilize infrastructure that are currently used, such as erosion control, will be needed all the more under wetter warmer scenarios. Therefore, the consequence of climate change further reinforces the rationale for existing management strategies for trail maintenance. However climate change in the form of more rain may overwhelm existing practices; hence one might say that current methods to control erosion may leave the trail system, and other infrastructure more vulnerable to damage (an example might be the Resurrection Trail near Exit Glacier)

It is possible that some activities on the forest could be managed more flexibly if the goal was to maximize ecosystem services from snow. For example, the current alternating year openings of the Resurrection Trail system to snowmachines might be adjusted to reflect snow conditions: If there is a good snow year, there could be a special opening for snowmachines during a nonmotorized year, and vice versa. This kind of regime is already practiced for personal use and commercial fisheries.

Maintaining recreation and tourism subsystems

When specific ecosystem services (snow) cannot be retained due to climate change, it may still be possible for the human activities and the associated economic livelihoods to shift, just as species can potentially move with shifting habitat. There are already mechanisms (e.g., cash reserves) available to accommodate short-term "shocks" to snow-dependent activities. Such mechanisms are mentioned in the tourism literature as being important to operators. For example, Biggs (2011) reports that based on survey data,

> reef tourism enterprises indicate that financial and marketing support are the most important actions that government can take to support enterprises in the face of a large shock. (Biggs 2011)

Snowmaking is a longer-term reaction to uncertain snowfall, which of course depends on water resources and sufficiently low temperature. Adding summer activity infrastructure is another strategy already adopted by many U.S. ski areas. One could perhaps think of the underlying "ecosystem service" as terrain rather than snow.

The tourism industry and resident recreation patterns have changed dramatically in the Chugach-Kenai SES during the past 20 years (Colt et al. 2002). These changes reflect shifting socioeconomic driver variables and an upsurge in entrepreneurial effort directed at providing nature-based tourism as a commercial product. The rapid deployment of people and capital seems to be a hallmark of these activities. Tourism businesses and their employees can and do move in response to changing conditions. While it is probably outside the management purview of the Forest Service to directly assist with this process as it is carried out by individuals, there may be a scope for easing transitions and accommodating change by focusing more on forest users and tourism businesses and less on the ecosystem services themselves. One example of this approach might be a more flexible fee structure for special use permits that recognizes the increased economic risk of running a snow-based business in the region.

Consequences of Potential Change in Snow and Glacier for Recreation Infrastructure

Changes to snow and ice, of all the biophysical changes evaluated in this vulnerability assessment, have the greatest potential to impact the condition of, and demand for, Chugach National Forest recreation infrastructure, particularly changes to snowfall and snowpack. Almost all of the developed recreation facilities, which includes cabins, campgrounds, day use sites, trailheads, and the roads and trails that provide access to them, are found between sea level and 1500m of elevation where projected changes to snow-day fraction, SWE, and snowpack vulnerability are the greatest. In PWS and the CRD, all recreation sites, trails, and roads are located between 0 and 500m in elevation, with most close to sea level. Currently, recreational use on the CNF is managed as snow-free (May 1 – November 30) and snow-based (December 1 – April 30) seasons. Where over-snow motorized vehicles are allowed, there must be adequate snow levels and conditions to prevent damage to vegetation and soils.

Impacts to Facilities

Snow and ice have resulted in damage to facilities in the past, including two cabins that sustained structural damage during heavy snowfalls in the winter of 2011-2012. Scenarios described above suggest that at elevations below 1500m, snow may put less pressure on structures across the CNF, especially cabins along the coastline in Prince William Sound and the Copper River Delta. At the same time, a decrease in snow-day fraction, especially in October and November, may extend the season of use for snow-free activities on trails that remain snow-free for a longer period of time; trails popular for hiking, mountain biking, and pack and saddle use may also be vulnerable to ruts, trail widening, and other impacts to trail tread due to a longer period of muddy conditions if rain replaces snow more often during the year. Where models project a possible change from snow dominant to transient hydrology, mostly along the coastline in Prince William Sound and in the Copper River Delta area, these changes may effect trail and trail bridge infrastructure depending on how nearby stream flow is affected.

Purpose or draw to the facility

Facilities that primarily support snow-based recreation or include glacier viewing would see the biggest change due to projected declines in snow days, SWE, and greater snowpack vulnerability, especially early and late in the winter. The Turnagain Pass facilities are the clearest example, as the two parking areas see more use in the winter as a backcountry skiing and snowmachining destination. While skiers could still use the site to access higher elevations by foot, snowmachines could not do the same. Approximately 20 miles of trails on the CNF are exclusively snow trails, all below 1500m in elevation. These trails may see less use, especially where motorized use is currently popular. Also, local volunteers have started to groom Russian River and Trail River campgrounds for Nordic skiing in the winter, an activity that would see a shorter season and more inconsistent conditions throughout the winter.

The Spencer Glacier Whistle Stop in the Kenai Mountains and Childs Glacier Campground along the Copper River were developed primarily for glacier viewing. Looking at projections in glacial retreat and thinning, these sites could face a similar situation as the Begich, Boggs Visitor Center (BBVC), where viewing Portage Glacier from the theater was the main draw. The glacier has been retreating for decades and is no longer visible from the BBVC. Due to this, as well as many other factors, visitation to the BBVC has declined from over 300,000 in the 1990s to around 70,000 in 2013.

Almost all of the campgrounds and day use sites, including picnic areas, campsites, trailheads, and boat ramps, are adjacent to the Seward, Sterling, Portage Glacier, and Copper River Highway. Turnagain Pass, at milepost 68 of the Seward Highway, is the highest point on this road system at an elevation of just over 300m. Campgrounds and most day use sites are primarily used in the snow-free season, especially between Memorial Day and Labor Day. Thus, the type and amount of use at these facilities is unlikely to see significant changes, though the shoulder seasons of use could potentially be extended later in the fall.

Access to facilities

Similar to changing patterns of the use of recreation sites, access to and from sites that are dependent on adequate snow conditions will be the most adversely affected, though no facilities and only about 20 miles of trail are used exclusively for snow-based recreation. On the other hand, where deep snowpack limits access or increases the challenge of using a facility, the season of use may expand. Cabins in PWS and the CRD areas may be easier to access and could see an increase in use with less snow, though snow is not the only limiting factor for use of these facilities. For instance, it still may not be desirable to be out in PWS in winter months when weather and seas are unpredictable. The cabins along Resurrection Pass Trail are popular in the winter for both skiers and snowmachiners; poor snow conditions make access by these means more difficult or impossible.

Adaptive capacity

Management of most recreation facilities on the CNF will be able to adapt to projected changes in snow and ice, since very few of them are used exclusively for snow-based activities and the vast majority of facilities are used more heavily in the snow-free months, especially between May to September. It is difficult to anticipate potential trends of snow-free activities, though, because multiple factors help make facilities popular at a given time during the year and current understanding of the behavior of recreationists is insufficient to make reasonable predictions. Thus, just being snow-free may not necessarily increase use. Overall, it is likely that facilities supporting winter, snow-based recreation will see a more significant decline in use than any corresponding increase in the use of infrastructure supporting snow-free recreation.

The least adaptable infrastructure would be motorized snow trails, since these are not used when snowpack is limited or inconsistent. At Spencer Glacier and Childs Glacier, summer recreation may still be popular and the potential to use facilities there does not change, but they may not have the same allure and visitors may be less likely to spend the money and effort to get to these remote locations.

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Tables

Table 1. Elevation bands, area, and snow-day fraction for Chugach National Forest

Elevation band	Pixels	Area (km²)	Historical[a] snow-day fraction (Oct. – Mar.), %	Projected[b] snow-day fraction (Oct. – Mar.), %	% change[c] (Oct. – Mar.)
0m	14612	8686	38.1	29.5	-22.7
1 – 500m	22361	13292	56.7	47.6	-16.0
501 – 1000m	14865	8836	71.1	62.5	-12.1
1001 – 1500m	9725	5781	80.6	72.8	-9.7
1501 – 2000m	2541	1511	86.4	80.2	-7.3
2001 – 2500m	971	577	91.7	87.3	-4.7
2501-3000m	368	219	95.4	92.7	-2.8
>3000m	44	26	97.8	96.4	-1.4

[a] 1970-1999 cool season average
[b] 2030-2059 cool season average, five GCM mean
[c] [(Projected – historical)/projected] * 100

Table 2. Historical SWE (1971-2000) and % change (5 GCM average, 2030-2059) by month and elevation band.

	Month											
	OCT		NOV		DEC		JAN		FEB		MAR	
Elevation Band	Hist. SWE (mm)	% change	Hist. SWE (mm)	% change	Hist. SWE (mm)	% change	Hist. SWE (mm)	% change	Hist. SWE (mm)	% change	Hist. SWE (mm)	% change
0 (sea level)	47	-45	84	-34	109	-8	105	-4	94	-24	70	-3
1 - 500m	58	-38	93	-22	117	-1	107	7	91	-13	73	3
501 - 1000m	155	-29	177	-13	215	4	184	11	156	-5	148	7
1001 - 1500m	274	-20	247	-8	293	5	250	12	216	1	222	9
1501 - 2000m	426	-9	307	-4	393	6	317	15	285	8	269	12
2001 - 2500m	684	0	443	-1	575	8	475	18	412	13	380	15
2501-3000m	758	6	465	2	603	9	492	19	438	17	387	15
>3000m	787	10	457	4	603	9	489	20	423	20	365	16

Table 3. Historical SWE, % change, and 5 model range for ONDJFM season.

	ONDJFM		
Elevation Band	**Hist. SWE (mm)**	**% change**	**model range (%)**
0 (sea level)	509	-20	-36 to -4
1 - 500m	539	-11	-22 to +1
501 - 1000m	1035	-4	-13 to +7
1001 - 1500m	1502	0	-9 to +10
1501 - 2000m	1998	5	-7 to +16
2001 - 2500m	2968	9	-5 to +21
2501-3000m	3143	11	-4 to +25
>3000m	3123	13	-3 to +20

Table 4. Changes in landscape fraction of snowpack vulnerability index classes for the Chugach National Forest Vulnerability Assessment domain estimated from coarse (0.5 degree) downscaled GCMs

	Snow dominant[a]	**Transient[b]**	**Rain dominant[c]**
Historical	92%	8%	0%
CCCMA-CGCM3.1 t47	76%	16%	8%
MPI-ECHAM5	76%	18%	5%
GFDL-CM2.1	76%	18%	5%
UKMOHadCM3	84%	16%	0%
MIROC3.2 medres	87%	8%	5%
5 model average	84%	13%	3%

[a] April 1 SWE / ONDJFM PPT > 0.4
[b] April 1 SWE / ONDJFM PPT between 0.1 and 0.4
[c] April 1 SWE / ONDJFM PPT < 0.1
* Rows may not add to 100% due to rounding.

Table 5. Changes in landscape fraction of snowpack vulnerability index classes for the Chugach National Forest Vulnerability Assessment domain estimated from fine (800m) downscaled GCMs

	Snow dominant[a]	Transient[b]	Rain dominant[c]
Historical	73%	27%	0%
CCCMA-CGCM3.1 t47	55%	45%	0%
MPI-ECHAM5	58%	42%	0%
GFDL-CM2.1	64%	36%	0%
UKMOHadCM3	67%	33%	0%
MIROC3.2 medres	65%	35%	0%
5 model average[d]	63%	37%	0%

[a] April 1 SWE / ONDJFM PPT > 0.4
[b] April 1 SWE / ONDJFM PPT between 0.1 and 0.4
[c] April 1 SWE / ONDJFM PPT < 0.1
[d] 5 model averages are not the average of the rows above, but are calculated for each pixel in the domain, and thus are slightly different than average of the five model summaries presented here.

Figures

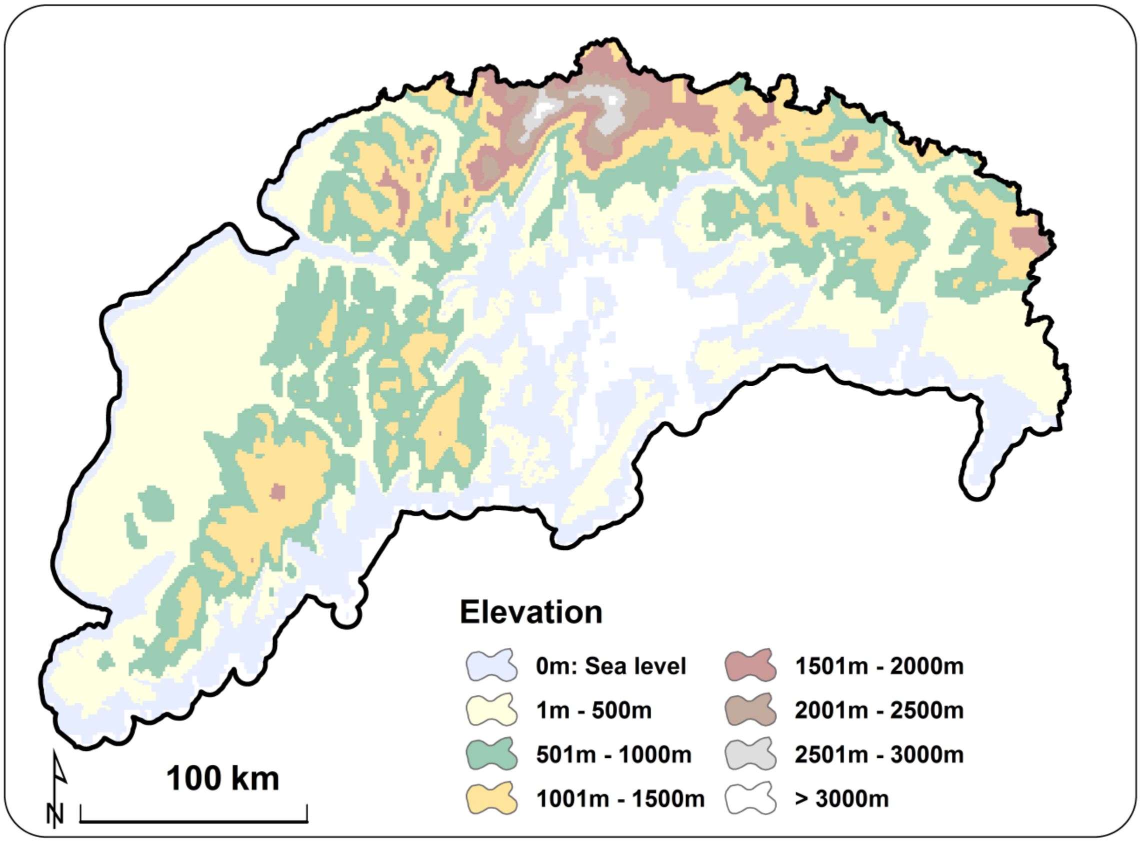


Figure 1. Elevation bands used in snow-day fraction analysis for Chugach National Forest.

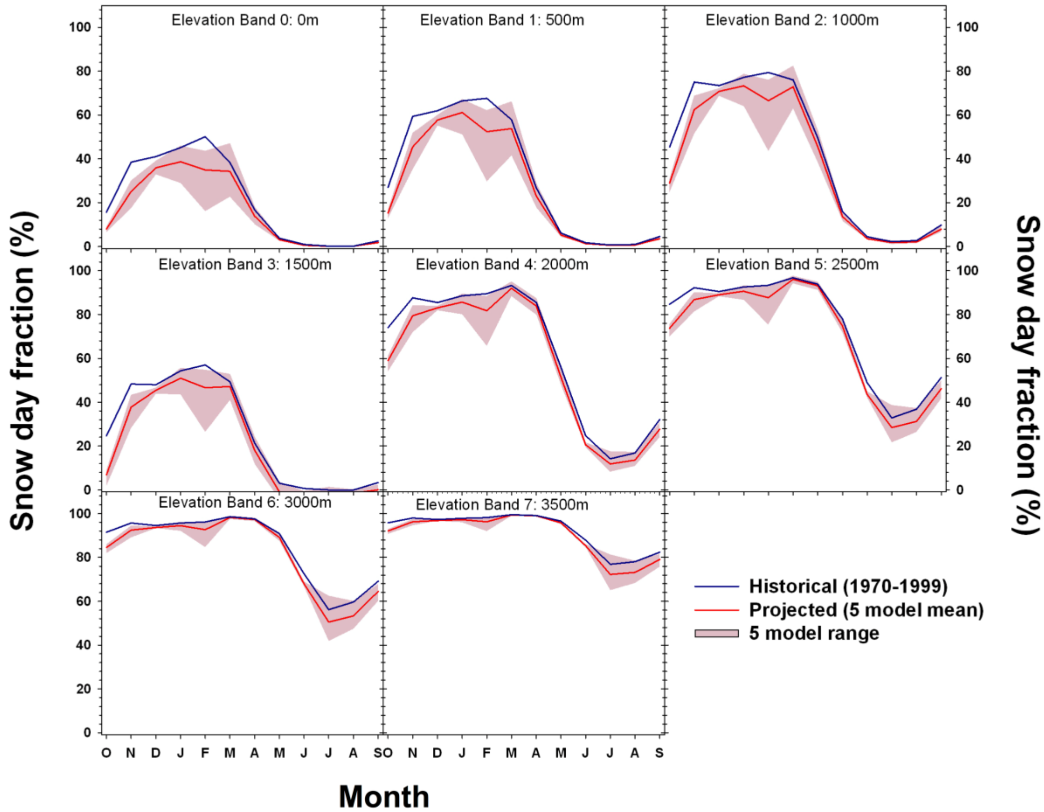


Figure 2. Historical (1971-2000) and projected (2030-2059) changes in mean monthly snow-day fraction by elevation band for the domain of the Chugach National Forest Vulnerability Assessment. Months are in "hydrologic year" order, October to September. Blue line indicates the historical average; red line indicates 5-model mean future average; pink area represents range of 5 future climate models.

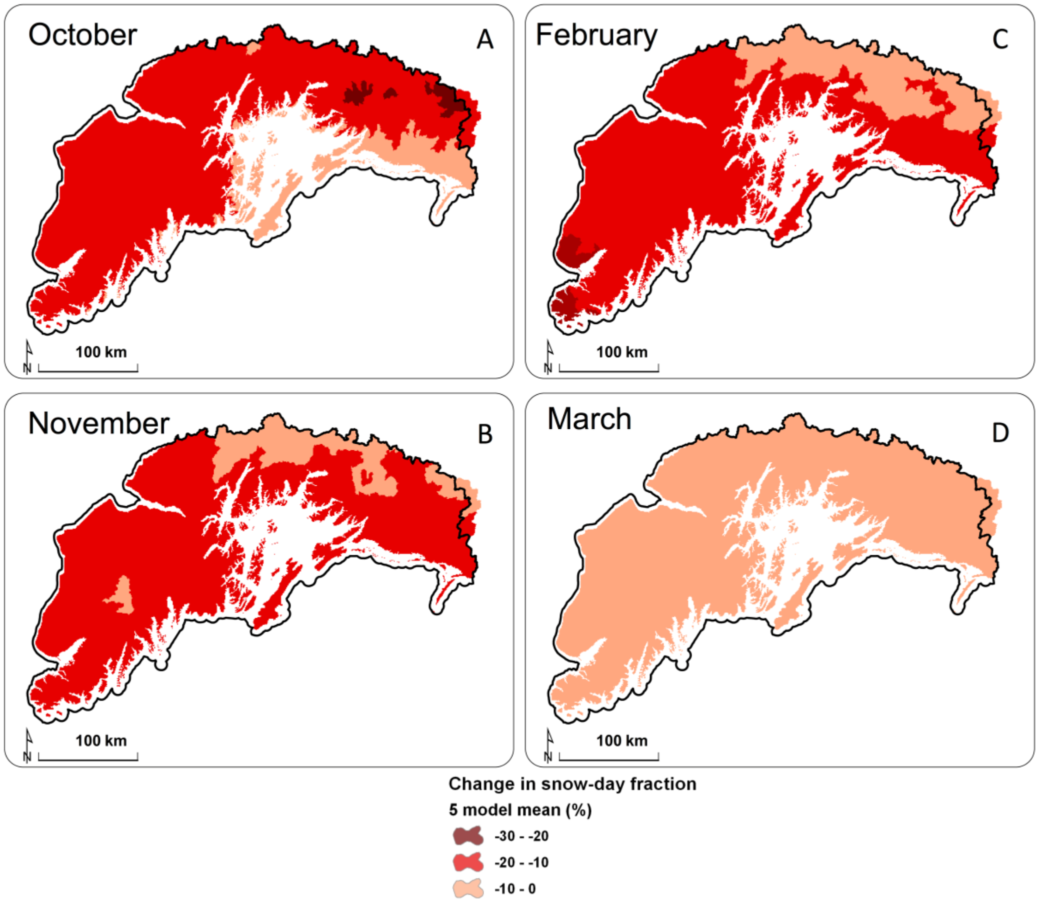


Figure 3. 2030-2059 changes in HUC-12 level mean snow-day fraction relative to historical (1971-2000) for selected months: (A) October, (B) November, (C) February and (D) March. The maps are focused on the domain of the Chugach National Forest Vulnerability Assessment, other lands are faded. Note that larger absolute declines at mid elevations from Figure 1 (between 500m and 2000m) in October (A) and at lower elevations (<500m) in November (B). Note that the percent values in the maps are raw declines, not percents of percents, such that a decrease from 60% to 30% and from 30% to 0% would get the same change but result in different absolute values.

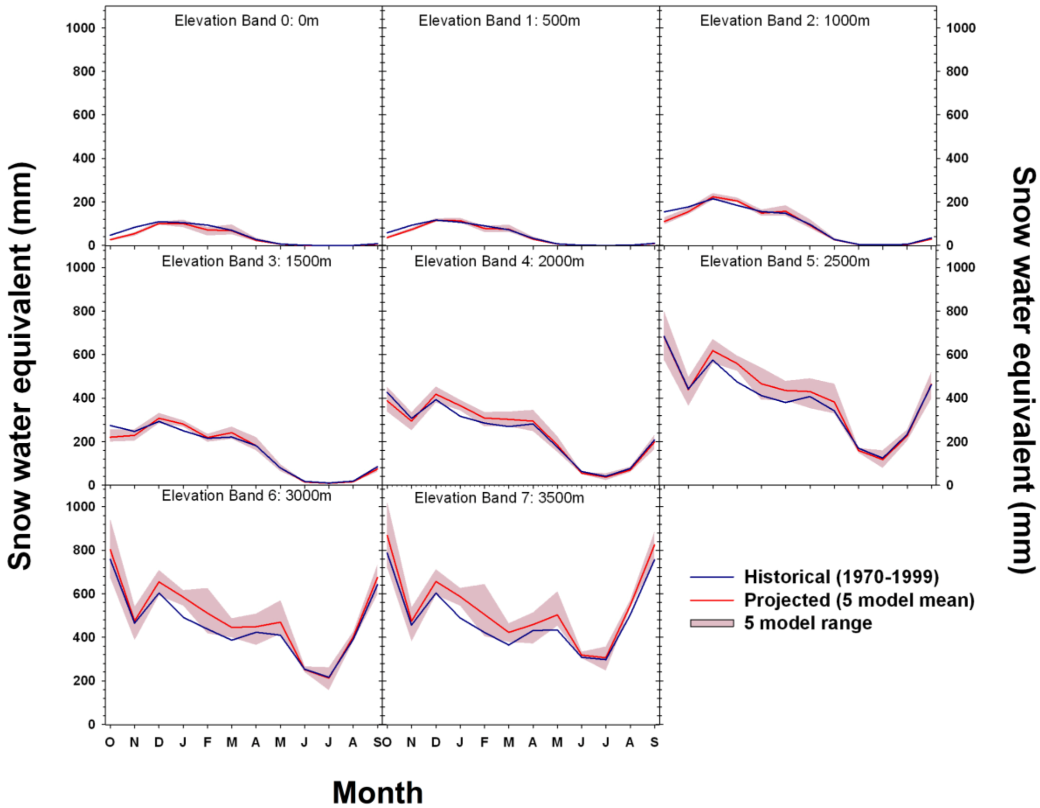


Figure 4. Historical (1971-2000) and projected (2030-2059) mean monthly snow water equivalent by elevation band for the domain of the Chugach National Forest Vulnerability Assessment. Months are in "hydrologic year" order, October to September. Blue line indicates the historical average; red line indicates 5-model mean future average; pink area represents range of 5 future climate models. Seasonal decreases in SWE are consistent with snowday fraction, including decreases in the autumn at elevations of 1500m and below, and possible increases in the winter months at elevations above 1500m.

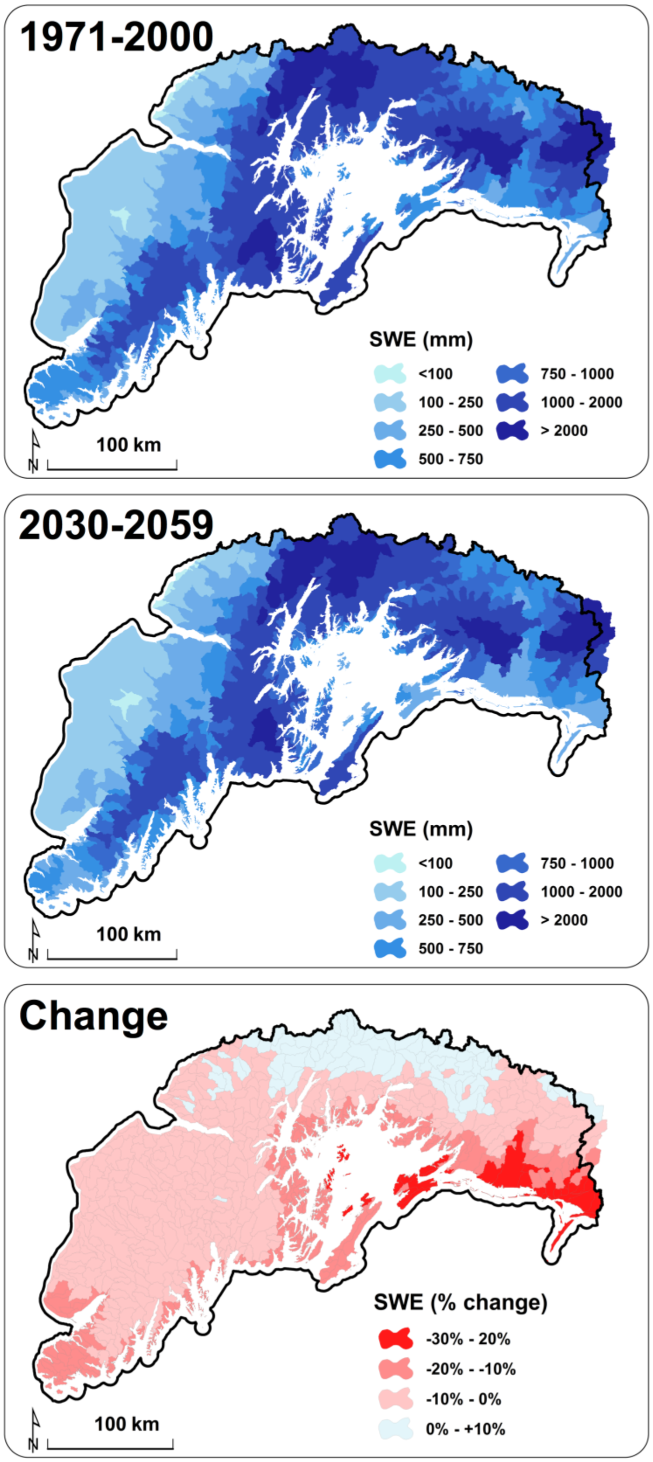


Figure 5. Historical (1971-2000, top) and projected future (2030-2059, mean of 5 GCMs, middle) ONDJFM SWE, with % change (bottom).

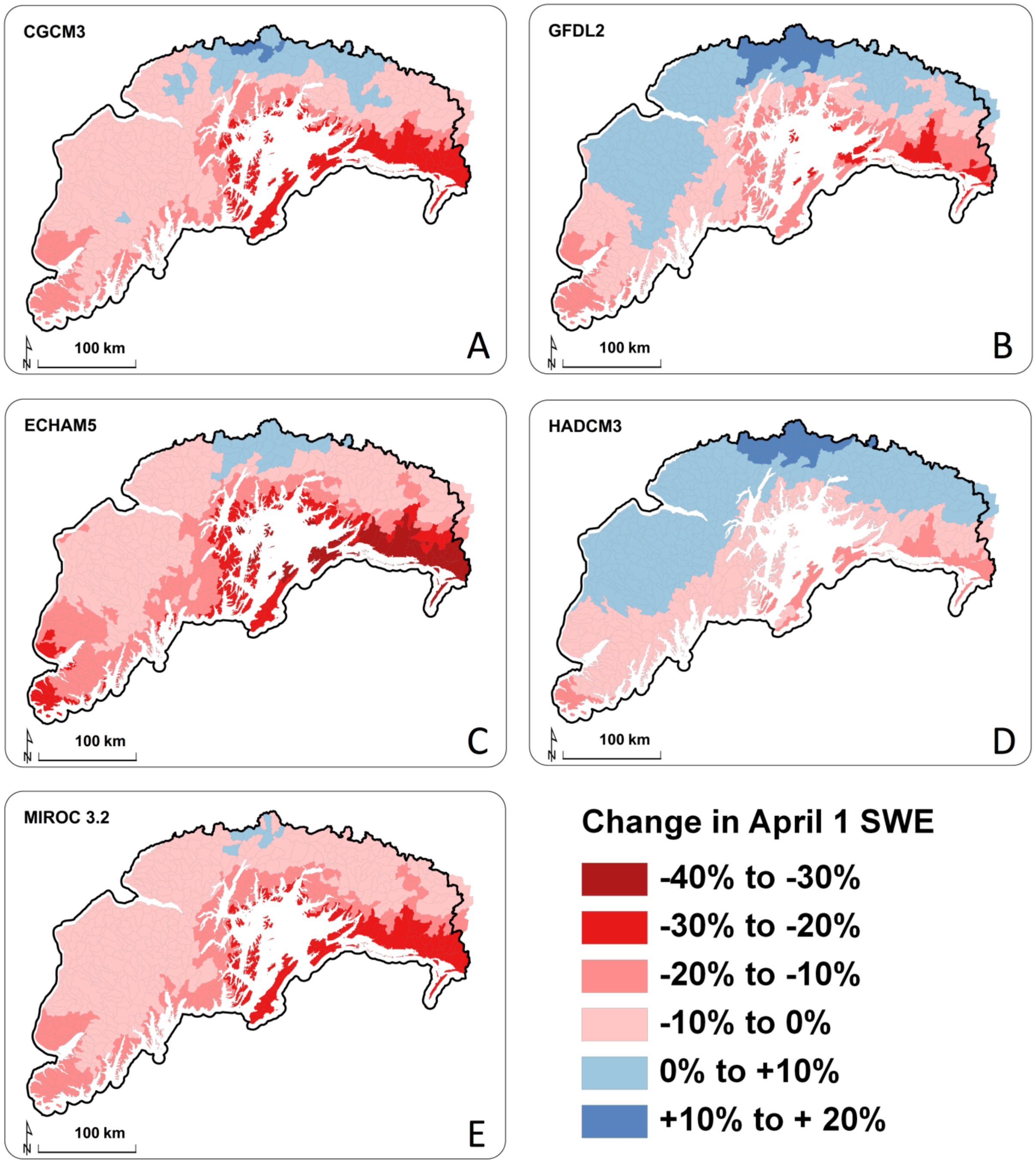


Figure 6. Projected changes in April 1 SWE (1971-2000 to 2030-2059) for five GCMs under the A2 emissions scenario: A) CGCM 3.1; B) GFDL CM 2.1; C) ECHAM 5; D) HadCM3; and E) Miroc 3.2 MedRes. Note that the percent values in the maps are percent change from historical SWE.

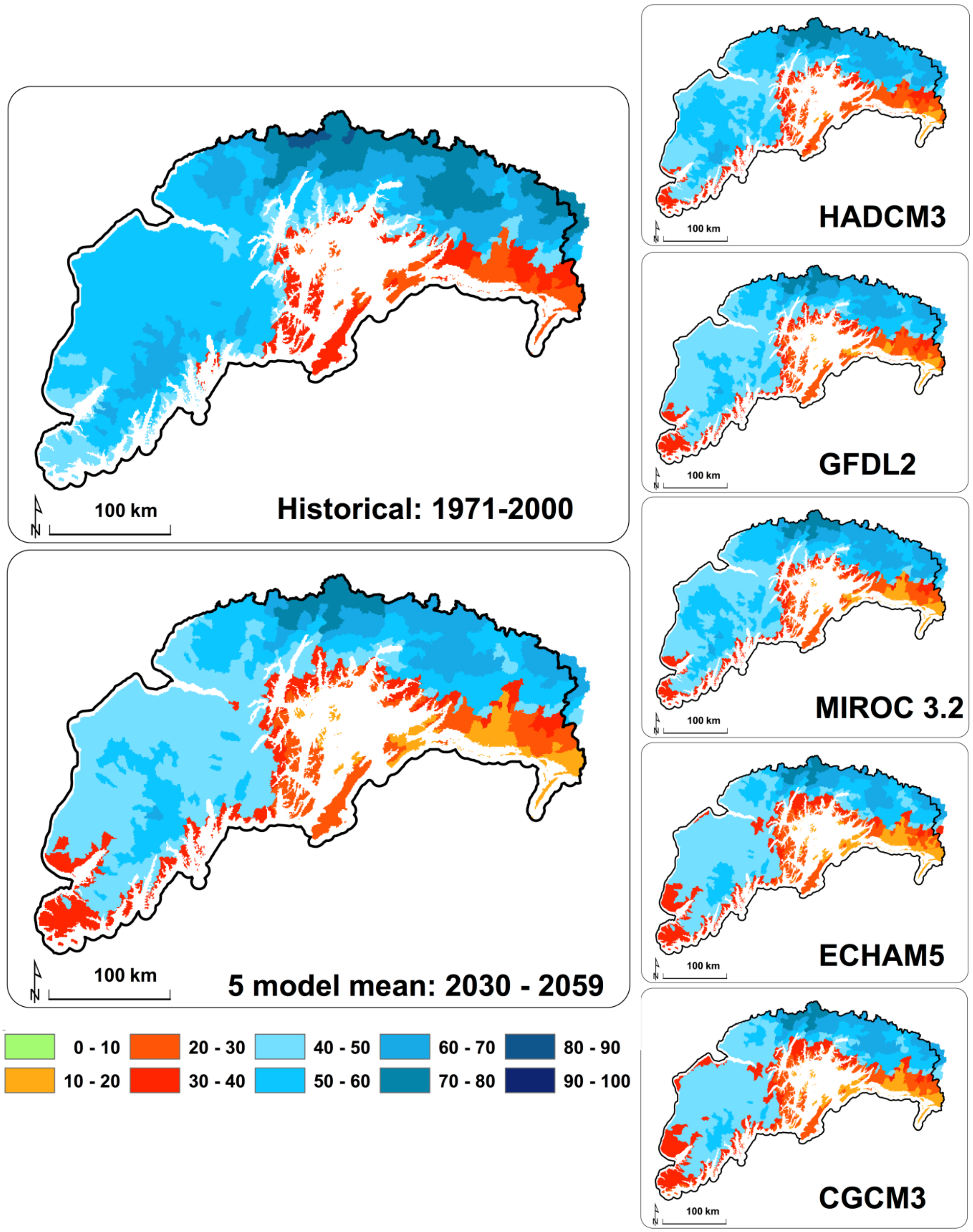


Figure 7. Projected changes in snowpack vulnerability index from SNAP historical (1971-2000) to 2030-2059) for five GCMs. Top left: Historical; Bottom left: five-model composite future; Right, from top: HadCM3, GFDL CM 2.1, Miroc 3.2 MedRes, ECHAM 5, CGCM 3.1. Note that "red" is transitional, where precipitation is a mix of rain and snow during the cool season and oranges indicate the precipitation is moving toward being rain dominant.

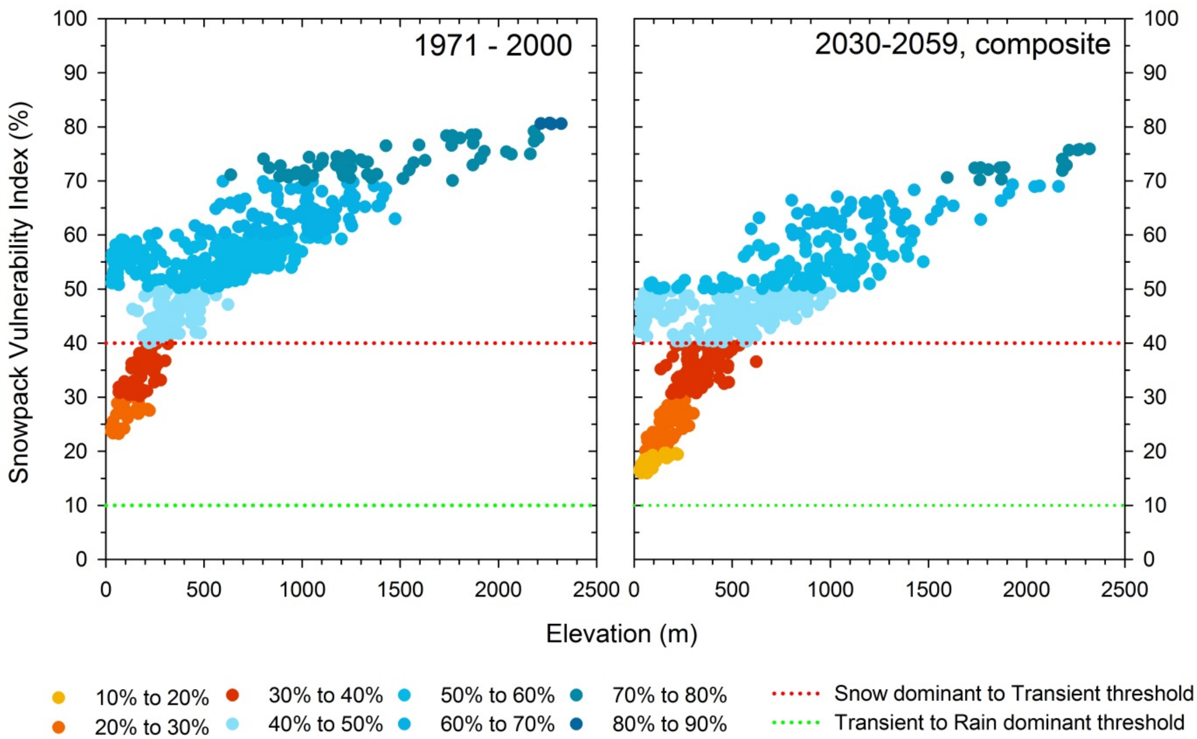


Figure 8. Snowpack vulnerability index for each Chugach domain HUC by elevation for historical and projected future period.

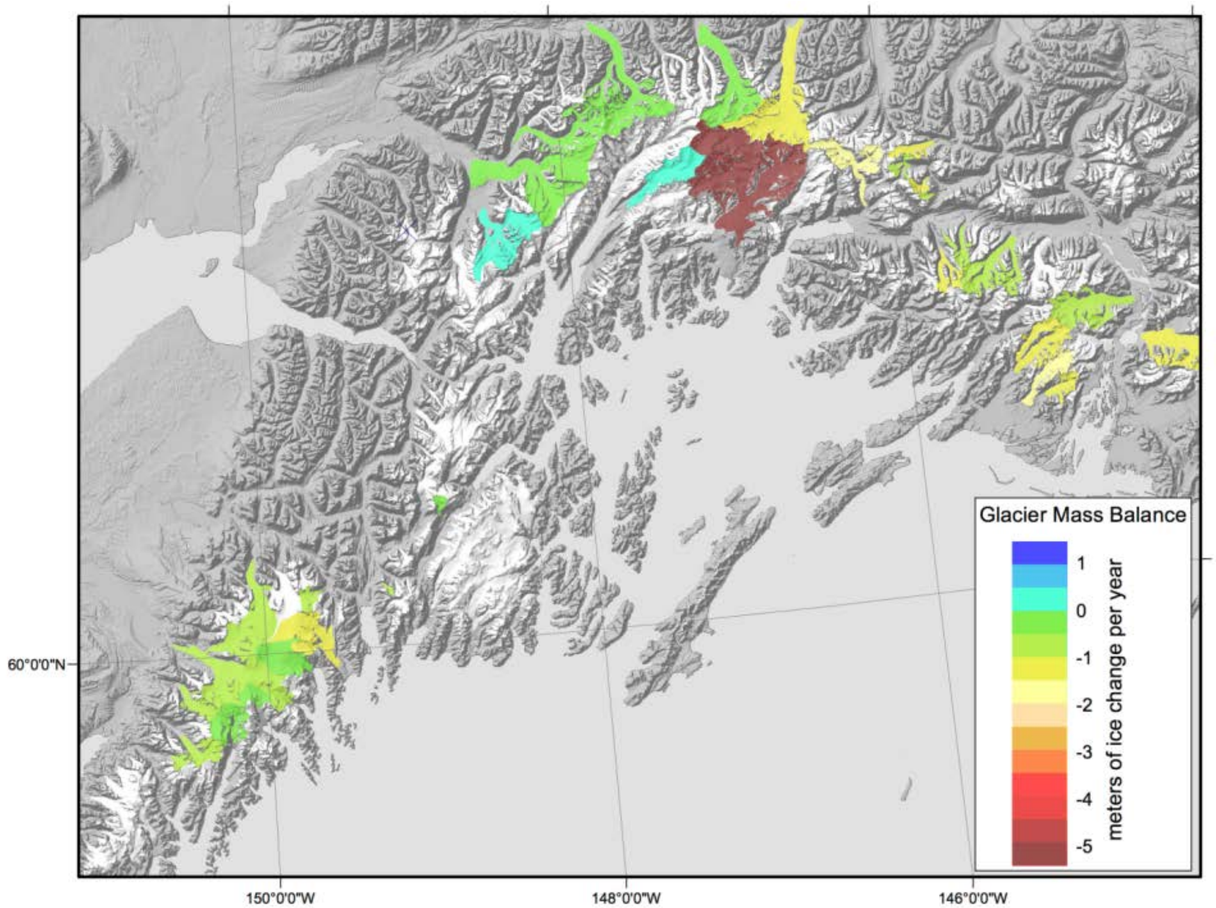


Figure 9. Volume of ice lost from glaciers in the CNF. Surveyed glaciers are colored, unsurveyed glaciers shown in white. Brick to green indicates mass loss, blue indicates mass gain. Note that short survey time frames (2009-2012) do not yet capture trends for some of these glaciers. (Larsen et al. 2015).

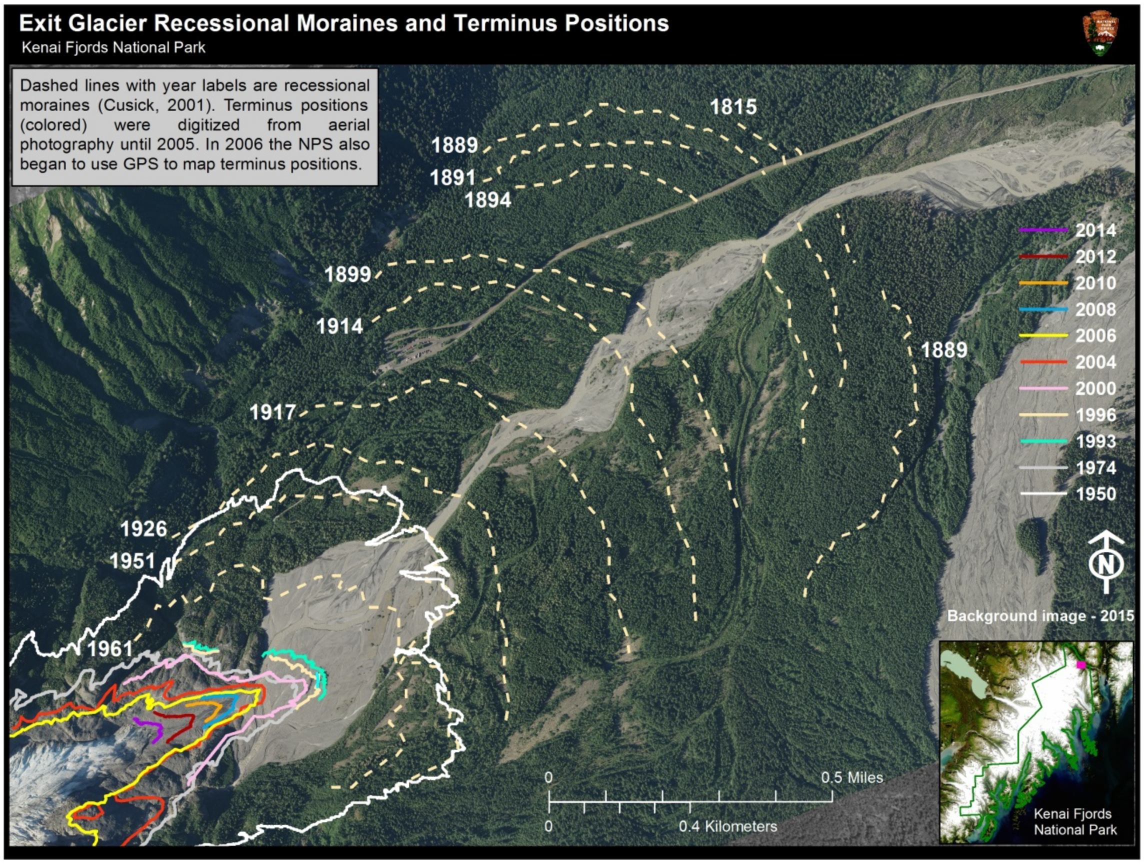


Figure 10 – Exit Glacier. Pattern of glacier recession at Exit Glacier, Kenai Fjords National Park, from 1815 to 2014

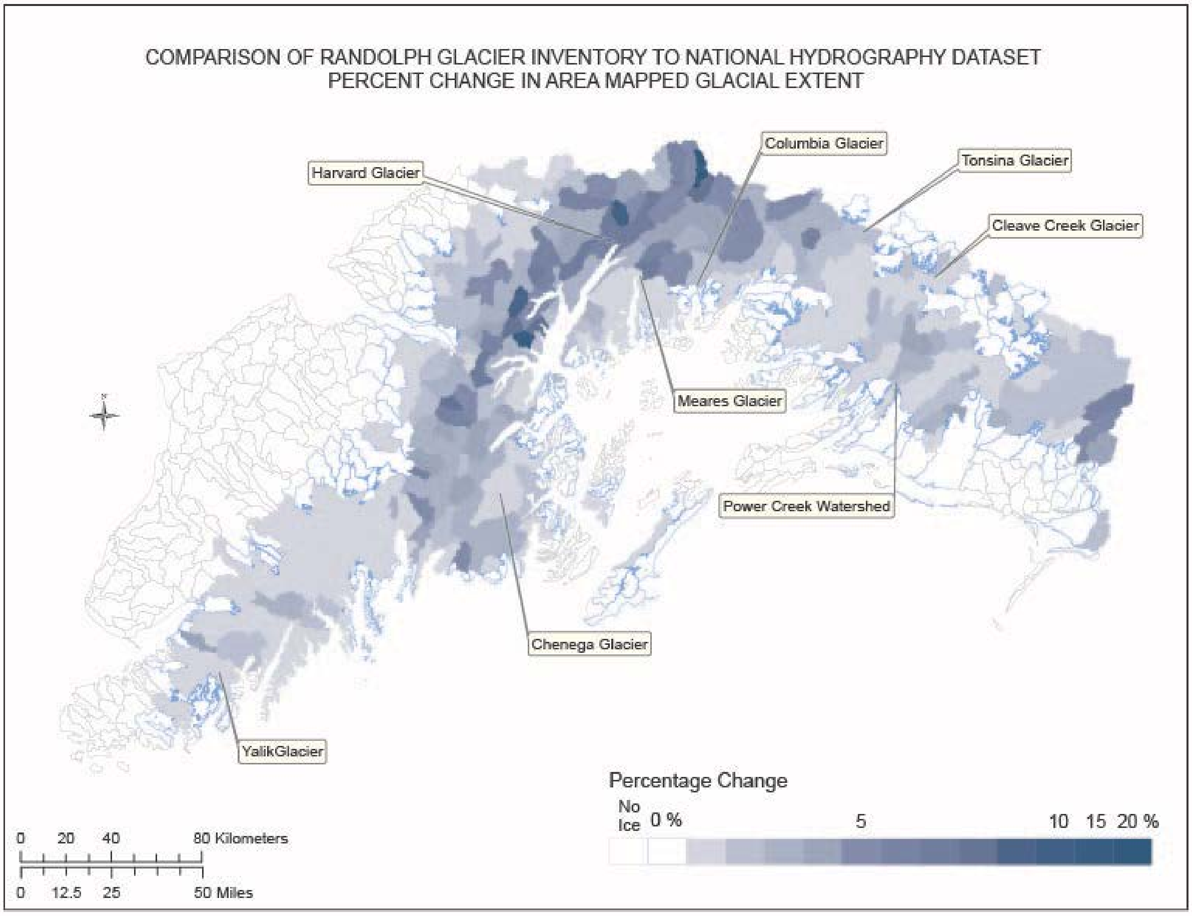
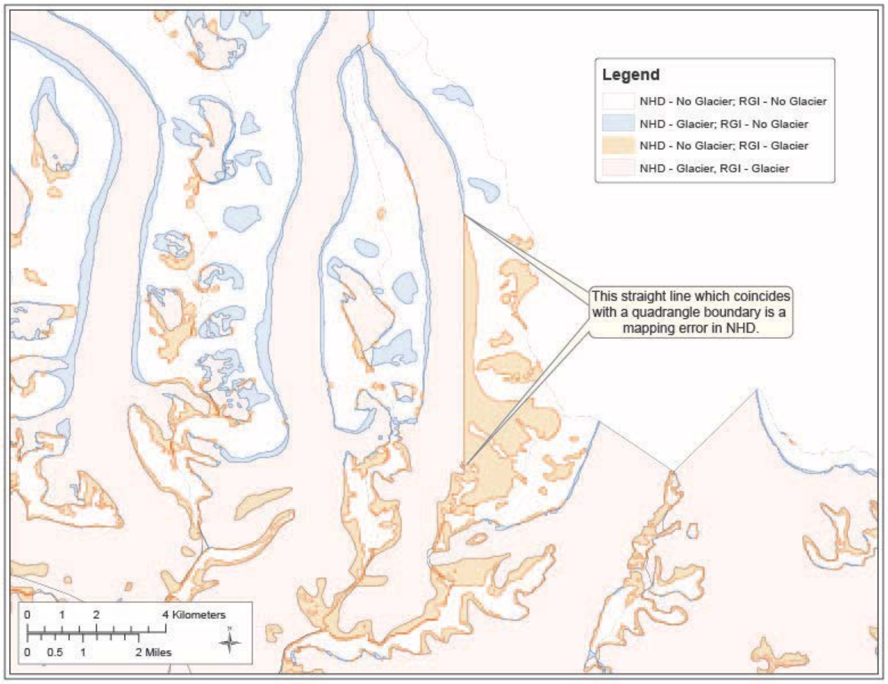


Figure 11 – Remote Sensing. Difference in the spatial extent of glaciers mapped using RGI and NHD. Here watersheds are classified by the extent to which RGI indicates ice present and NHD indicates ice is not present. Interpretation of this difference might suggest that glaciers may be advancing which has been documented for Harvard and Mears Glaciers, but is questionable in other places. Map: Linda Kelly, USFS.



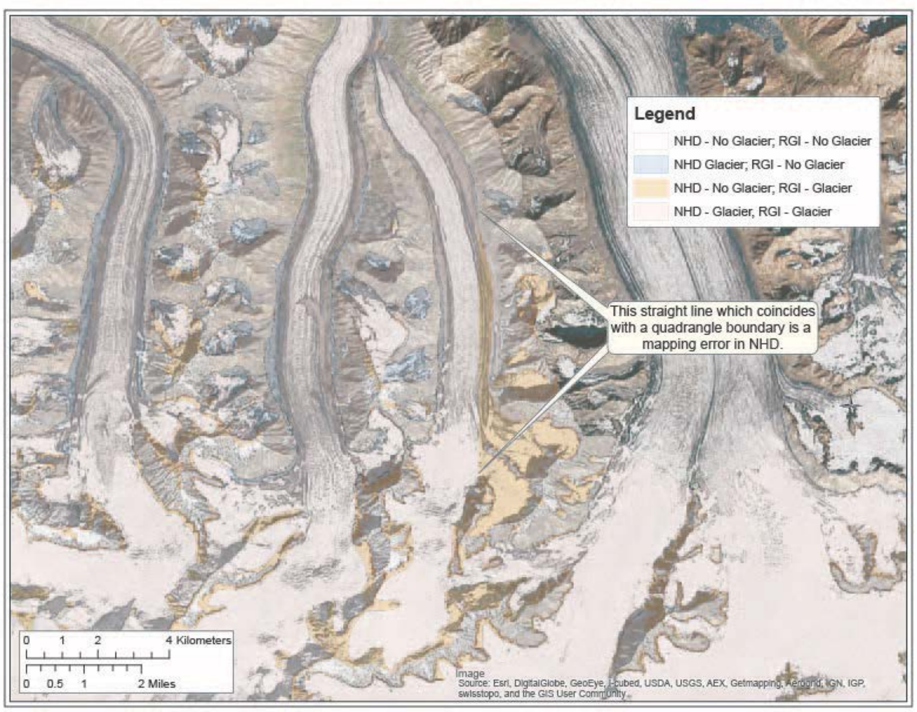


Figure 12 – Remote Sensing. Tarr Glacier Watershed illustrating an approach to validate differences in glacier extent measured using RGI and NHD data overlaying a photography base. The differences between the mapped glacial margins illustrates an occurrence where a programmatic comparison falsely suggests glacier expansion due to mapping errors. Map: Linda Kelly, USFS.

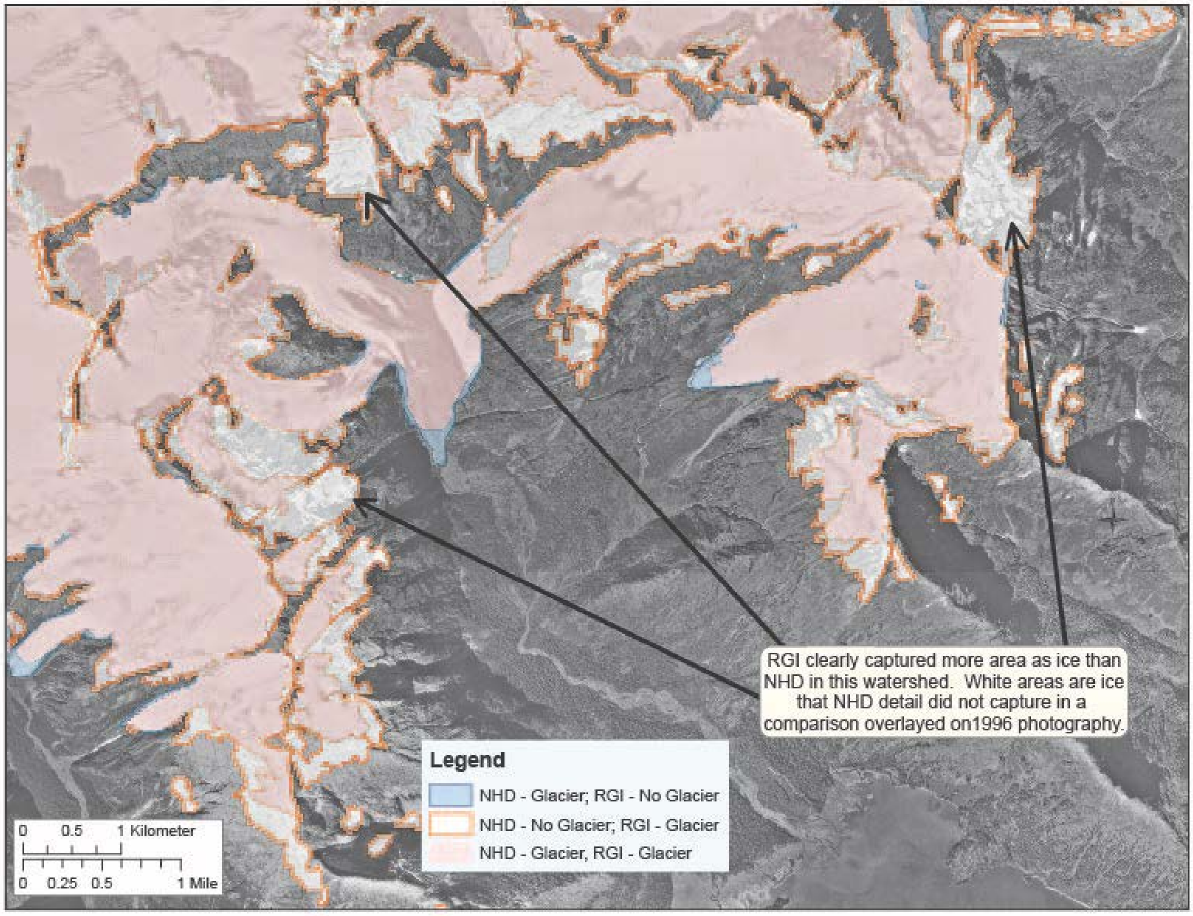


Figure 13 – Remote Sensing. Pigot Glacier Watershed illustrating an approach to validate differences in glacier extent measured using RGI and NHD maps employing black and white photography from 1996. RGI maps 15 percent greater glacier extent than NHD but this difference is largely due to errors in NHD where there was a failure to map some glacial features. Map: Linda Kelly, USFS.

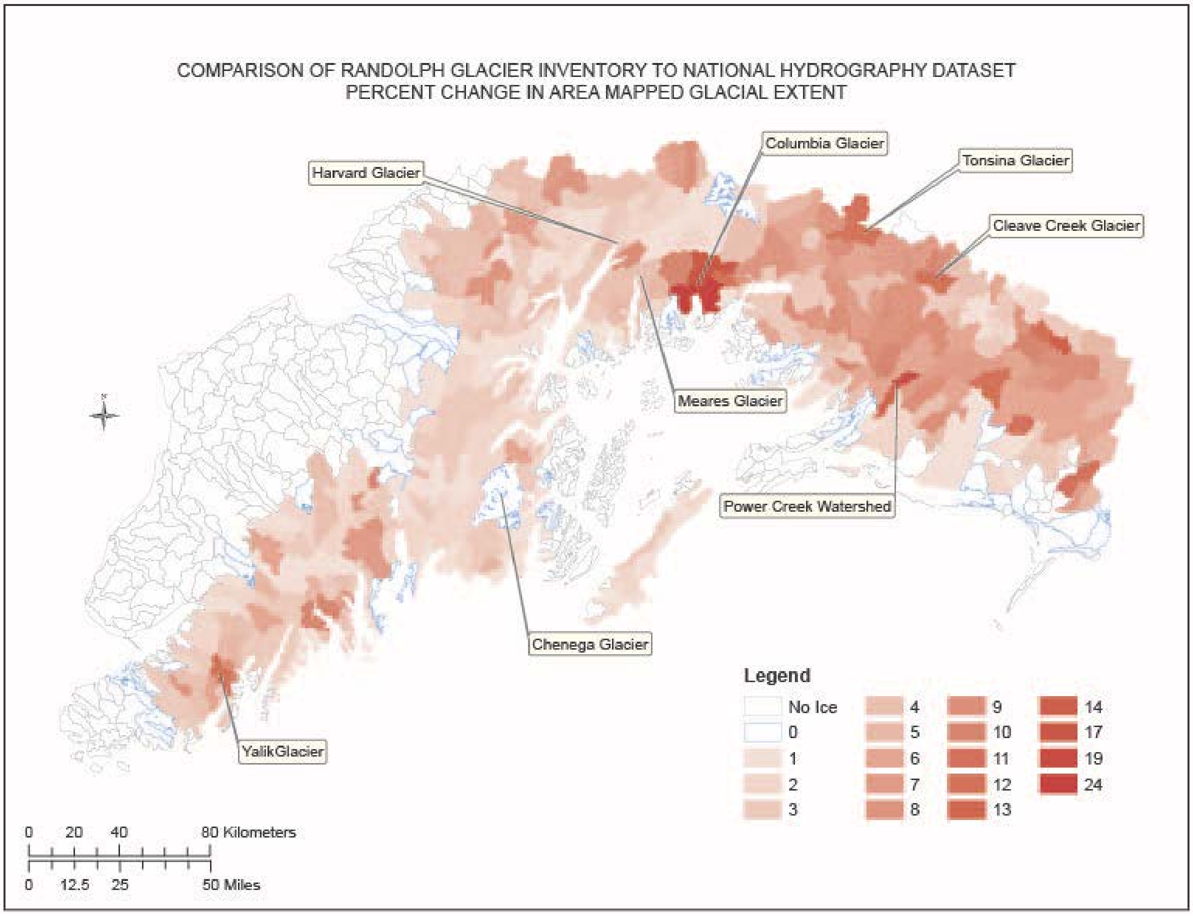


Figure 14 – Remote Sensing. Illustration examining estimation of ice loss resulting from comparison of NHD and RGI products at Columbia Glacier and surrounding areas. Verification with photography suggests that pattern of ice loss illustrated by comparing RGI and NHD in this case is valid.

Chapter 4: SEASCAPES

Andrew Erickson[1], Claire Colegrove[1], Aaron Poe[2]

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[2] U S Fish and Wildlife Service, Aleutian and Bering Sea Islands Landscape Conservation Cooperative

Summary

- The Chugach/Kenai coastline stretches for 3,890 miles, including islands and the Prince William Sound.
- Coasts and marine environments within the assessment area receive heavy human use from tourism, fishing, and local economic activity. Understanding how coastal environments will be affected by climate change is important for land management planning.
- Important abiotic effects of climate change on the coastal environment include sea level change, glacial changes, and ocean acidification.
- The trends for the region show sea level decline at rates of up to a fraction of an inch per year, resulting in changes to tidal marshes and barrier islands.
- Prince William Sound receives up to 50% of its freshwater discharge from glacial runoff, indicating that changes to the region's tidewater glaciers will have profound effects on the coastal environment.
- Cold ocean temperatures make Alaska's oceans particularly vulnerable to ocean acidification, but biotic communities in Prince William Sound, the Copper River Delta, and the Kenai coast may be resilient due to their ability to cope with high physical and chemical variability likely due to seasonal freshwater influx.
- Important biotic effects of climate change include harmful algal blooms, changes to eel grass beds, and effects on shorebirds.
- Warmer waters and glacial melt may exacerbate harmful algal blooms, which pose a threat to shellfisheries in the assessment area.
- Eelgrass beds are abundant within the assessment area and are susceptible to changes in water depth, and human-caused disturbances.
- Prince William Sound and the Copper River Delta are two of the most visited stopover locations for migrating shorebirds, which are vulnerable to loss of mudflats caused by sea level change.

Introduction

The assessment area is predominantly a coastal landscape. Its 3,890-mile shoreline encompasses Prince William Sound and numerous islands, connecting the upland forest ecosystem to the Pacific Ocean through rocky beaches, marsh tidelands, eelgrass beds, and tidewater glaciers. As an important part of the Chugach/Kenai landscape, the coastal ecosystem deserves significant attention from the region's scientists and policy-makers.

Although this dynamic coastal landscape (Harwell et al. 2010) is accustomed to extremes in physical conditions – it frequently experiences powerful storms, extremely variable wave action, seasonal changes in weather, and many forms of pulse-stressors – climate change presents the potential for chronic change in the ecosystem (Haufler et al. 2010). Climate-induced abiotic changes including ocean acidification, increased air and ocean temperatures, altered precipitation patterns, and dynamic sea level conditions are likely to affect coastal environments (Ainsworth et al. 2011, Melack et al. 1997). As outlined elsewhere in this assessment (see Chapter 3) snow and glacier covered portions of the assessment area are currently experiencing altered temperature and precipitation patterns, resulting in changes to seasonal snow cover and the extent of glaciers. The directional changes in abiotic factors are likely to affect biotic characteristics of the Chugach coastal ecosystem, including species diversity and distribution, and introduction of pioneering or exotic species into climate-disturbed areas (Haufler et al. 2010).

This chapter provides a primer on the issues and environmental conditions affecting the coastal ecosystem of the assessment area. We examine an array of climate-induced changes in ocean and coastal conditions, including abiotic and biotic effects of climate change. The chapter is particularly motivated by the understanding that human use of the assessment area, notably Prince William Sound and the eastern Kenai, primarily occurs within the marine environment with the coast serving as the viewscape of both visitors and those who make a living from the marine environment Given the importance of the coast and it's varied environments to tourists, fishermen, and the biota of both the land and sea, examining potential influences of climate change is critical to the larger assessment. However, the chapter's scope is limited by the rapidly developing scientific understanding of the coastal ecosystem and our capacity to distill the complex biological, physical, and chemical processes into a useful tool for land managers. Our intent is not to outline the broad array of environmental processes affecting the Chugach coast. Instead, this chapter aims to draw attention to several changes that land managers and the public should be aware of and to identify issues where more comprehensive and rigorous evaluation could be beneficial.

Chugach Seascapes

The coasts are among the most accessible and visited parts of the Chugach National Forest. Since its creation in 1907, a central focus of the Chugach has been to provide visitors with the opportunity to experience unrivaled landscapes, wildlife encounters, and recreational opportunities (USFS 2011). But because the high mountain ranges and inaccessible terrain constrain land transportation throughout the forest, the traditional point of access has been through the coast. Ferries, cruise ships, smaller private vessels, and aircraft provide access throughout the assessment area for residents and visitors (Poe and Greenwood 2010). Tourism, fishing, and recreation are the dominant uses of public lands in the assessment area (Poe et al. 2010a) and a majority of this use, particularly when cruise ship viewing is included, originates from the marine environment.

In order to conceptualize changes occurring over such a vast and diverse coast, we divide the coastal ecosystem into three geographical areas, which we call "seascapes" (fig. 1). A seascape consists of more than just the beach – it is the capillary zone where upland forests transition to the ocean. The spatial extent of seascapes are variable though typically considered to be a large areas where conditions in the ocean affect upland habitats and vice versa. Each seascape has unique physical and biological characteristics, ecological processes, and human environments (The LCC Network 2014). The aesthetic quality of seascapes and the enjoyment of such by visitors in ocean craft result in some important characteristics of seascapes extending far inland.

The western seascape consists of the upper Kenai Peninsula, beginning in the high alpine peaks of the Chugach Mountains and extending 150 miles southwest. The Kenai Peninsula is separated from the mainland of Alaska on the west by Cook Inlet and Prince William Sound on the east. The Kenai is widely recognized for its stunning scenery, world-class fishing, wildlife viewing, and outdoor recreation (USFS 2002).

The central seascape consists of the western, northern, and eastern coasts of Prince William Sound, including the many islands within the sound. This seascape is characterized by shallow straits, long fjords, protected bays, diverse tidal zones, and forested shores. The area is home to a diverse biologic community including seabirds, shorebirds, fish (all five Pacific species of salmon), sea otters, harbor seals, Stellar sea lions, orcas, and gray and humpback whales. Cruise ships of all sizes travel through the sound, offering tourists the chance to see glaciers and wildlife. Commercial, sport, and subsistence fishing are all significant economic drivers of the Prince William Sound human environment (Harwell et al. 2010, Jewett and Duffy 2007).

The northwestern portion of the seascape sees the highest degree of human use on the forest itself with most access occurring by small, privately owned motorized boat. There is also commercial outfitter and guide activity that accesses forest land in this region by small motorized boat and kayak. It is authorized by the Forest under special use permit and when compared to overall vessel use only represents about ~10% of the total small boat traffic in the region(Poe at al. 2010a). Subsistence harvest, primarily of fish and marine species occurs throughout this region but occurs most frequently in the vicinity of the communities of Cordova, Chenega Bay, Tatitlek and Whittier (Poe et al. 2010b). Downloadable map galleries and data sets are available at http://www.fs.usda.gov/detail/chugach/landmanagement/planning/?cid=stelprdb5139741.

The eastern seascape consists of the Copper River Delta, which stretches across 700,000 acres and drains an area of 26,500 square miles. The delta is a large and very significant wetlands complex on North America's Pacific coast. The delta seascape's most distinct ecological features are its barrier islands, which create shallows that support large populations of marine invertebrates and provide a haulout and nesting ground for marine mammals and birds. In the spring, the delta is a globally significant staging ground for 16-20 million migratory birds (USFS 2014). Nearly the entire Pacific coast population of dunlins and western sandpipers rely on the delta for habitat (Bishop et al. 2000). Other important bird species in the delta seascape include sandpipers, knots, Canada geese, and swans (Isleib and Kessel 1973).

In the following sections we highlight some of the broad abiotic and biotic effects of climate change that are likely to alter the Chugach's seascapes.

Abiotic Effects of Climate Change

As outlined earlier in this Assessment (Chapters 2 and 3) the climate of southcentral Alaska is expected to warm during the next 20 to 40 years, leading to higher winter and summer temperatures, reductions in snowpack at lower elevations, reductions in glacier mass volume and spatial extent, and a longer growing season (Haufler et al. 2010, Keyser et al. 2000, Larsen et al. 2007). As a result of the changing climate, abiotic conditions within the Chugach's seascapes are expected to change, which in turn will affect seascape biological communities and human uses (Haufler et al. 2010). We focus on three important abiotic effects of climate change: sea level change, glacial changes, and ocean acidification.

Sea Level Change

Alaska has more than 44,000 miles of shoreline, more than twice that of the lower 48 states combined (Glick et al. 2010). With such a large coast, Alaska as a whole is exposed to the potential consequences of sea-level rise over the long-term. But importantly, the coasts across the assessment area are unlikely to experience large sea level rises (Clark et al. 1977, Dean 2009, Haufler et al. 2010).

The broad current trends for the assessment area show the sea level in this region has been falling at rates of up to a fraction of an inch per year. This decrease is caused in part by ocean circulation shifts in response to changes in wind stress at the eastern boundary of the North Pacific. The decreasing sea levels in the assessment area are largely the result of long time-scale patterns of isostatic rebound and geologic activity.

Isostatic rebound occurs when melting glaciers cause the release pressure from the ice triggering uplift in the land (Larsen et al. 2005). In the assessment area, glaciers that dominate the seascapes have been diminishing in extent and mass for thousands of years,, resulting long-term uplift of the underlying land.

Studies conducted on the Kenai Peninsula show regional isostatic rebound rates of 0.4 in/yr, and peak uplift rates for southeast Alaska exceed 1.2 in/yr. The rate of isostatic rebound for the Kenai Peninsula is 3 times faster than global average sea-level rise; throughout southeast Alaska, isostatic rebound is occurring 10 times faster than sea-level rise.

Geologic activity and resulting tectonic movement is also a major contributor to local changes in sea level in the region. Southcentral Alaska experienced dramatic tectonic movement associated with the historic 9.2 magnitude earthquake in 1964 (Haufler et al. 2010). As a result, some areas of the coast sank while others experienced significant uplift. Because the Chugach/Kenai region contains both areas of uplift and subsidence, local changes in sea level are likely to vary along the coastline. For example, the Copper River Delta is subsiding at approximately 1.2 mm/yr (Garrett et al. 2014).

Although isostatic rebound and geologic activity have suppressed sea- level rise in the Gulf of Alaska since the mid-1970s (Bromirski et al. 2011), the trend in stable or falling sea level is not projected in the extremely long term. Isostatic rebound slows once glaciers have melted substantially, tectonic uplift can be reversed by another major earthquake, and it is likely that the Northeast Pacific circulation will change again, all of which would result in a period of sea level rise substantially faster than the global average (Bromirski et al. 2011).

The potential consequences of changing sea level are especially apparent in the Copper River Delta. The delta seascape contains a large percentage of all the tidal marshes in southcentral Alaska. Tidal marshes can occur wherever there is flat land at sea level (Frohn, 1953). Three elements are required for tidal marsh formation: 1) the input of tidal waters, 2) sediment deposition, and 3) protection from ocean wave and ocean-current erosion (Boggs et al. 2008). Tidal marshes and the adjoining mudflats are one of Alaska's most important habitats as staging areas for millions of migrating shorebirds, geese, and swans. The marshes and mudflats also support species of concern like dusky Canada goose (*Branta canadensis occidentalis*), Western sandpiper (*Calidris mauri*), and dunlin (*Calidris alpina*).

Changes in relative sea level have a dramatic effect on tidal marshes and other coastal ecosystems. Along a subsiding coastline, tidal marshes may migrate inland inundating formally non-tidal sites such as forests or peatlands. At the same time, tidal communities along an outer marsh may erode or drown completely. Tidal marshes where coastal areas are stable or subsiding appear to be some of the most vulnerable habitats to sea level rise in the Chugach National Forest.

Barrier islands within the assessment may also be vulnerable to the effects of sea level change. In other parts of Alaska these islands are also threatened by coastal erosion and inundation as a result of changes in frequency and intensity of coastal storms (Meehan et al. 2012). Barrier islands are sandy coastal islands separated from the mainland by an estuary or bay (fig. 2). They are uncommon in southern Alaska and typically occur near large river deltas, such as the Copper River Delta (Boggs 2000, DeVelice and Juday 2007, Hayes and Ruby 1994). Although barrier islands are created by processes similar to those that created spits, they are unique in that barrier island separation from the mainland reduces access by predators such as brown bears and wolves. Consequently, barrier islands provide protected haulouts for harbor seals, stopover feeding grounds for migrating shorebirds, and habitat for a variety of bird species, including the Glaucous-winged gull (*Larus glaucesens*) and dusky Canada goose (Sowls et al. 1978).

The barrier islands of the Copper River Delta range up to 2 km in width and 13 km in length and typically rise less than 30 ft above sea level (Thilenius 1990) (fig. 3). Sand and silt are delivered to the coast by the Copper River where the sediment is transferred to the marine environment and deposited on the deltas. Longshore currents, which generate waves that strike beaches obliquely, move sediment parallel to these currents. Waves redistribute sediment across the beach profile and wind erodes depositional features and transports the sand downwind. High wave energy environments suspend silt and transport it to lower energy depositional environments. Consequently, sand forms beaches and dunes along the high energy seaward side of islands, and silt forms tidal marshes and tide flats along the leeward, low energy estuary side of islands (fig. 4).

During storms, portions of barrier islands and spits are often inundated and subjected to wave action known as overwash. Sand is transported from the beach and deposited further inland on the island or spit. Depending on the severity of the storm, overwash may affect the front portion of the landform or completely breach low portions. In the latter case, sediment is deposited on the back side of the landform as a washover fan (Ritter 1986).

Distinct landform and vegetation patterns are common among barrier islands. Low-gradient beaches emerge from the ocean and transition to sparsely vegetated dunes, taller back dunes dominated by herbaceous vegetation, and wetlands. Behind the tall back dunes, elevation tapers toward the estuary where vegetation grades to uplifted tidal marshes, tidal marshes, and tide flats. Pioneer species such as dune grass (*Leymus mollis*) stabilize the sand with roots that penetrate more than 3 ft to the water table (Boggs 2000, DeVelice and Juday, 2007). Species and plant association diversity increases with dune stability. Herbaceous associations include fireweed (*Chamerion angustifolium*), beach strawberry (*Fragaria chiloensis*), dune grass/boreal yarrow (*Leymus mollis*/*Achillea borealis*), and lupin (*Lupinus nootkatensis*).

Loss of barrier island habitat from climate-induced sea level change is difficult to predict; projections must account for local trends of tectonic uplift and subsidence, the potential for seismic repositioning of the shoreline and glacial rebound. In general, barrier islands represent dynamic habitats capable of repositioning, growing, and shrinking in response to changing conditions.

Glacial Changes

The second major abiotic effect of climate change in the Chugach seascape is glacial change. Alaska's glaciers are one of the main attractions for tourists in Alaska. Cruise ships and charter boats bring thousands of visitors to view tidewater glaciers each year. Glaciers provide remote recreational opportunities, including world class ice and alpine climbing, skiing, and glacier trekking while also serving an important ecological function in the Chugach seascape (Timm et al. 2014) (see Chapter 3) Melting glaciers drive the Alaska coastal current, bring nutrients to the ocean, and drive the hydrology of many river ecosystems (Astrom et al. 2014).

Although some of Alaska's glaciers are growing, taken as a whole, the state's glaciers are experiencing an overall loss of between 40 and 70 Gt/yr (Kaser et al. 2006). The first statewide survey of glacier volume change completed in 2002 estimated an ice loss of 13 mi/yr from the 1950s to the mid-1990s, and a rate that is expected to doubles in the next five years (Marken et al. 2012).

The most dynamic glaciers are the low-lying tidewater glaciers (Larsen et al. 2007). The coastal ecosystems created by the interface of glacier runoff and marine environment located at the terminus of tidewater glaciers result in highly productive, heterotrophic systems (Hood and Scott 2008). Changes in climate affect glaciers in complex ways, resulting in mass balance changes that will differ across the assessment area. In the past, the pattern of glacier growth and decline, or modulation appears to have occurred primarily at temporal scales of many decades to centuries for most glaciers superimposed upon the millennium-scale dynamics of glacial and interglacial periods. Human-induced climate change affects this balance, and modeling (see Chapters 2 and 3) shows the zone of accumulation pushed higher in elevation. At the highest elevations, precipitation increases substantially and temperatures stay below freezing for much of the year, and it is possible for glaciers to increase in mass balance. The ultimate status of each glacier depends on the long-term outcome of the balance between accumulation at high elevations and loss at lower elevations.

The Prince William Sound coastal region is particularly influenced by climate change because such a significant portion of its freshwater discharge, about 50%, is derived from glacial runoff (Neal et al. 2010). The iron supplied by the glacial dust suspended in this freshwater discharge is critical to phytoplankton production in this region. Changes in the dynamics of this ecosystem have implications on nutrient delivery that affects primary productivity and subsequent fish, shellfish, and marine bird and mammal populations. Currently, krill and plankton thrive in glacier-dominated fjords, but the productivity stems from the nutrient content of the sediment loads derived from upstream glacial action. Seabirds and harbor seals feeding at tidewater glacier termini show a high fidelity to glacial habitat because of the availability of food and sea ice haul outs to protect themselves from predators.

These same areas are also a focal point for marine recreation and tourism, particularly with respect to tidewater glaciers (Poe at al. 2010a), where higher levels of human use overlap with some species of conservation concern (Suring and Poe 2010). Decreases in the biological productivity of these systems as they become less influenced by the presence of glacier ice will have significant implications for species and likely also for their desirability as recreation and tourism destinations (O'Neel et al. 2014). Conversely in the short term as glaciers retreat they open up new beaches and recently denuded terrain as new potential recreation locations; this has been observed in the vicinity of Columbia Glacier.

In southcentral Alaska, unlike areas supporting continental glaciers, understanding the impacts of climate change on glaciers is complicated by the fact that glaciers in different situations respond differently to the same regional changes in climate. Elevation, association with ice fields, and whether a glacier's terminus is in tidewater affect how the glacier will respond to temperature and precipitation changes.

Ocean Acidification

The third major abiotic effect of climate change affecting Chugach seascapes is ocean acidification. The world's oceans play the dominant role in global dynamics of the carbon cycle through the uptake and chemical processing of carbon dioxide (CO_2). Through biological and chemical processes, oceans absorb nearly a third of the carbon dioxide emitted every year (Wackernagel et al. 2002). Although ocean capture of CO_2 has buffered the terrestrial world from more significant atmospheric warming, carbon dioxide in the oceans moves into a dynamic system involving both biotic and abiotic pathways with a small portion being sequestered in sediments as plants or animals sink to the bottom of the ocean and get buried. Most of the CO_2 remains dissolved into the surface seawater, forming carbonic acid. Over the past 250 years, as atmospheric CO2 has increased, the pH of the ocean has decreased by 0.1 units (from 8.2 to 8.1), corresponding to a 30% increase in acidity, with projected increases at a rate of 0.5% to 1.0% per year. Changes in acidity have major consequences for marine life by reducing the availability of carbonate ions that many marine organisms use to build shells and external skeletons. The colder temperatures of Alaska's oceans make them particularly vulnerable to ocean acidification.

The assessment area experiences an extremely complex pattern of ocean currents, freshwater input, and tidal movements. As a result, spatial and temporal variation in pH (and other physical and chemical features of the water) is extreme. Consequently, the organisms within Prince William Sound, along the Copper River Delta/marine interface, and along the Kenai coast, experience high variability in physical and chemical conditions. It is difficult to predict how this inherent variability will interact with directional changes in pH to influence marine life.

Biotic Effects of Climate Change

The abiotic changes in the assessment area are likely to affect biotic characteristics of the coastal ecosystem. This section highlights the effects of climate change on biotic communities within the Chugach seascapes. We focus on harmful algal blooms, which are an emerging threat within the Alaska coastal environment changes to eel grass beds and effects on shorebird populations.

Harmful Algal Blooms

Harmful algal blooms (HABs) involving toxic phytoplankton have recently emerged as a threat to commercial and subsistence shellfisheries in parts of Alaska (Anderson et al. 2000). Unlike the other phenomena addressed in this chapter, increased greenhouse gas emissions are not a direct driver of harmful algal blooms; however, there are several mechanisms by which climate changes are expected to exacerbate the threat from HABs. As a result, the potential exists for HABs to spread or become more frequent in the coastal areas of the Chugach.

There are several mechanisms by which climate changes could increase the threat of harmful algal blooms in the coastal areas of the assessment area. Warmer coastal waters, rapid melt of glaciers resulting in iron rich dust blowing into ocean waters providing a critical micronutrient for algae, and ocean acidification may favor organisms which do not have calcium carbonate shells, including dinoflagellates and diatoms, over more beneficial plankton types (Gao and Campbell 2013).

Beyond the public health threat of HABs, health problems associated with phytoplankton have also occurred in humpback and right whales, northern fulmar, great cormorant, herring gull, common tern, common murre, Pacific loon, and sooty shearwater. Mortality of sea lions, seals, sea otters, dolphins, a sperm whale, minke whale, and large numbers of birds, including grebes, gulls, cormorants, American avocets, loons, and sooty shearwaters, have also been associated with algal blooms.

Eelgrass Beds

Eelgrass *Zostera marina* L. appears in abundant meadows and beds throughout Alaska where sand and mud substrates occur in sheltered estuarine environments (fig. 5). Mundy (2005) described eelgrass as one of the primary sources of food in the northern Gulf of Alaska along with phytoplankton, macroalgae and detritus. Macroalgae and eelgrass are the primary groups providing biomass to the near-shore zone, followed closely by shallow and deep infauna, deep epibenthos, and herbivorous zooplankton. The rich and varied eelgrass environment provides significant primary production and stability for sediments as well as varied substrate, cover and food for invertebrates and vertebrates (Cowardin et al. 1979, Dean et al. 1998, Dean et al. 2000, McRoy 1970). Within Prince William Sound (described by Harwell et al. (2010) as "a semi-enclosed fjord estuary on the southern coast of Alaska"), eelgrass beds are an important component of the nearshore ecosystem (Dean et al. 1998). The diverse biota supported by the extensive vegetation and associated detritus are comprised of microfaunal species (foraminifera, ciliates, and other protozoans) (Mundy 2005) and meiofauna (nematodes, harpacticoid copepods, and turbellarians) (Feder and Paul 1980a, Feder and Paul 1980b). Some of the more recognizable macroinvertebrates include gastropods, bivalves, polychaetes, and amphipods living in and among the dense rhizome masses, and on and among the leaves (Jewett et al. 1999). Dean et al. (1998) reviews the literature documenting the rich assemblage of invertebrates, fish and birds using eelgrass beds for food and shelter, including economically important species of crabs and fish. Hughes et al. (2014) provide an extensive list of the fish and key invertebrates that use eelgrass beds as nursery grounds at critical life stages. It is clearly understandable that Johnson et al. (2003) considered eelgrass beds as essential fish habitat serving as nursery grounds for both salmon and key species of groundfish.

Many shorebirds, sea ducks, and seabirds make use of the nutrition contained in eelgrass beds during different seasons. Perhaps the best-documented example is from the Izembek Lagoon located at Cold Bay on the Alaska Peninsula where nearly the entire world's population of Pacific brant and Taverner's Canada geese (Ward et al. 1997) use the lagoon's eelgrass meadows. Prince William Sound eelgrass bed use by birds is less documented but the beds are no doubt used extensively by resident birds and by species making their way north and south on annual migrations. Marine mammals and land mammals also forage in eelgrass beds on abundant prey in certain locations. More specifically, sea otters and harbor seals forage in eelgrass beds (Ward et al. 1997) and, at low tide in the Izembek Lagoon, brown bears have been seen foraging in the exposed eelgrass beds (Ward, pers.comm.).

Potential consequences of climate change on eelgrass ecosystems may be inferred from past research. Potential stressors include changes in water temperature, salinity, pH, and depth. Studies conducted in Izembek Lagoon (Biebl and McRoy 1971) demonstrate remarkable resilience of eelgrass beds to broad fluctuations in temperature. Sharp declines in photosynthesis were not observed until temperatures of 30-35 C were reached. Biebl and McRoy (1971) distinguished between subtidal and tidepool forms of eelgrass beds with the tidepool form having a capacity to withstand 35-40 C before photosynthesis declined. The study further indicated that, while eelgrass survived well in freshwater for up to 10 days without visible damage, the plants died in 24 hours when exposed to 4.0 X seawater salinity (Biebl and McRoy 1971). Based on these studies, it appears unlikely that eelgrass beds in Prince William Sound will be severely affected by anticipated climate change effects of increased marine temperature (e.g. Abdul-Aziz et al. 2011) and changing salinities.

Eelgrass favors the soft sediments of shallow, protected lagoons and is excluded from large river deltas and glacial fjords (Hall 1988). Changes in salinity due to either fresh water intrusion from melting glaciers or increasing salinity in areas that may be isolated and affected by rising temperatures may have little effect due to the high tolerance of the eelgrass to changes in both decreased and increased salinities. Less is known about the response of eelgrass to changes in pH. Change in pH will influence the broader eelgrass system, however, through effects on dominant fauna such as calcareous invertebrates, and perhaps the soft bodied invertebrates that inhabit eelgrass beds. The abundant invertebrates that use eelgrass for cover and food, and that are less tolerant to the short and long term changes in pH may respond most directly to climate change and indirectly influence eelgrass systems.

Eelgrass is susceptible to changes in water depth. Water clarity affected by turbidity and depth of light attenuation affects the bathymetric distribution of eelgrass. Shaughnessy et al. (2012) reported the eelgrass depth range was 0.9 to -1.6 m for the sheltered Izembek Lagoon with respect to the mean lower low water (MLLW). In a study conducted near Juneau, Alaska, Harris et al. (2008) found the distribution of eelgrass from 2.0 to -2.8 m. relative to MLLW. In Denmark the historical distribution for eelgrass was 5.6 to11 m depth with the recent distribution reduced to between 2.5 and 8 m depth in sheltered and exposed areas respectively (Baden et al. 2003). However, significant changes in effective sea level are not expected over the next 40 years as a result of climate change (see *Sea Level Change* this chapter). Should water levels rise or descend substantially in the assessment area, it will most likely be due to tectonic activity. Post-glacial rebound is likely to ameliorate significant relative sea level rises in Alaska (NOAA Climate Program Office 2012). For the immediate future, submergence of the eelgrass beds to an unfavorable depth due to climate change effects is unlikely.

The most significant and immediate threats to eelgrass beds are from more immediate anthropogenic sources such as dredging, vessel groundings and other disturbances, and pollution (Ward et al. 1997); although, at least one example of eelgrass beds oiled by the *Exxon Valdez* oil spill demonstrated rather remarkable resilience and recovered relatively quickly (Dean et al. 1998). However, based on the studies following the oil spill, the species occurring with eelgrass, are likely to be more susceptible to pollution within this habitat. However, it is quite possible the community could be recolonized by zoochore and hydrochore dispersal of invertebrates and their larvae from within the sound if the eelgrass beds remain largely intact.

It would appear that eelgrass meadows and beds, with their apparent resilience, will continue to provide habitat and nourishment for the associated invertebrates, fish, birds and wildlife that use the resource despite changes in marine conditions anticipated over the next 40 years.

Shorebirds

Shorebirds represent a dominant ecological and social taxonomic group associated with the Chugach/Kenai seascapes. The coastline of Prince William Sound, and particularly the Copper River Delta, is one of the most visited stopover locations for birds migrating to northern breeding grounds in the spring. The Chugach/Kenai coastline is separated from the valleys of interior Alaska by sheer slopes of the Chugach and Kenai mountain ranges, and that restrictive topography combined with climate and biogeography makes it an ideal place for shorebirds to feed and rest due to abundant food and feeding habitat at a critical location along the migratory route. An estimated 5 million shorebirds visit the Copper River Delta each spring; the largest concentration in the Western hemisphere (Alaska Shorebird Group

2008). Over 73 different species of shorebirds have been documented in Alaska and most move through the Chugach/Kenai region. Consequently, a third of the world's shorebird species have been recorded here (Alaska Shorebird Group 2008).

Globally, shorebirds populations have declined significantly since 2000 (Alaska Shorebird Group 2008). In Alaska, shorebirds face potential threats as well as positive changes in environment from habitat shifts due to sea level change, glacial retreat and associated changes in hydrology, uplifted marshes, and increased storm activity, as well as potential changes in food availability due to ocean temperature changes, ocean acidification, and phenological shifts that may decouple food abundance with the arrival of the migratory birds. Key shorebird species of current conservation concern in the region, with further vulnerability compounded by climate change, include black oystercatcher (*Haematopus bachmani*), surfbird (*Calidris virgata*), red-necked phalarope (*Phalaropus lobatus*), western sandpiper (*Calidris mauri*), and red knot (*Calidris canutus roselaari*).

There are several anticipated climate related changes that could impact shorebird populations along the Chugach National Forest shoreline. One of the clear concerns for western sandpiper is the potential inundation of intertidal mudflats, which could eliminate both feeding and nesting habitat. Because of their low gradient and location at the transition from ocean to land, intertidal mud flats are susceptible to the slightest shift in sea level. A significant increase in sea level would inundate large areas of current mudflats. The availability of this critical habitat type, therefore, would depend on the rate of mudflat formation in areas currently existing as upland habitat. This interplay between sea level rise and mudflat status is especially complex in the assessment area. Increased storm surges influence the dynamics of mudflats; large storms can inundate substantial portions of tidal mudflats potentially effecting food across large proportions of foraging areas.

Bird migration is also likely to be affected by climate change. Ocean and air temperature changes can cause a phenological changes, causing birds to arrive in the feeding stopovers when food is least abundant, which can lead to many shorebirds not making the final leg to their breeding grounds. Changes in ocean conditions such as shifts in temperature or acidity can also impact food availability in areas where it has previously been plentiful for shorebirds (Visser and Both 2005).

It is estimated that there are fewer than 11,000 black oystercatchers worldwide and over half of them are known to nest in Alaska, particularly concentrated around Prince William Sound (Morrison et al. 2006, Tessler et al. 2007). The species is listed as a species of high concern in the Alaskan, national, and Canadian shorebird conservation plans (Brown et al. 2001, Alaska Shorebird Group 2008, Donaldson et al. 2000). Black oystercatchers exhibit strong breeding site fidelity which makes their reproduction particularly sensitive to environmental changes (Andres 1998) and potential disturbance by human use of shorelines (Poe et al. 2009). Black oystercatchers nest in a restricted area between the high tide line and coastal vegetation or on islets just above high tide. Consequently, nests are vulnerable to surging storm tides. Other potential interactions with climate change include changes in abundance of dominant food species (molluscs and bivalves) that may decline in abundance if marine pH declines significantly.

Following the *Exxon Valdez* oil spill, black oystercatcher populations were examined carefully because they appeared to be one of the species to recover most slowly (Andres 1997, Murphy and Mabee 2000). The life history of black oystercatchers, particularly low recruitment of young, suggests relatively long recovery periods following any major mortality events. On the other hand, long life-span suggests that population growth of the species is most sensitive to adult mortality which provides some buffer to loss of reproduction in individual years. This large shorebird has demonstrated resilience to the major ecological disturbance following the *Exxon Valdez* spill. Furthermore, the species demonstrated an ability to disperse into, occupy, and increase in new habitat following the development of open shore habitat on Middleton Island resulting from the 1964 earthquake (Gill et al. 2004).

Several of the many species of shorebirds that use the region for migratory stopover habitat are worth highlighting: these include the surfbird, red-necked phalarope, western sandpiper, and red knot. The surfbird also has a relatively small global population estimated at 70,000 (Senner and McCaffery 1997). More than three quarters of all surfbirds breed in Alaska, north of the assessment area (Senner and McCaffery 1997). Prince William Sound coastline provides one of the most important staging grounds for surfbirds during spring migration. Migrating surfbirds depend on herring spawn and mollusks for food during critical stopovers during their long migration along the Pacific coast of North and South America (Brown et al. 2001). Both prey types experienced steep declines in availability after the *Exxon Valdez* oil spill. (e.g. Jewett, et al. 1999, Shigenaka 2014, Thorne and Thomas 2008)Pacific herring spawning around Prince William Sound has historically occurred in mid-April when water temperatures reach around 39 F (Cooney et al. 2001). The eggs are attached to underwater vegetation near shore. Once deposited many herring eggs experience immediate mortality from heavy wave action and smothering (Cooney et al. 2001). An increase in large waves from storm surges could increase herring spawn mortality. Studies have shown that the majority of egg deposition in Prince William Sound occurs around northern Montague Island and a few eastern and northern sites (Norcross et al. 2001). In a study completed on northern Montague Island in 1994 scientists found that surfbirds accounted for a large percentage of the birds observed in the herring spawning areas and their arrival occurred shortly after spawning (Bishop 1996). If the herring spawn earlier, triggered by warmer ocean temperatures, surfbirds, and other migratory herring spawn feeders in this area, like black turnstones (*Arenaria melanocephala*), must adjust migration timing to take advantage of this food. The potential phenological mismatch is made especially possible by herring spawn's short incubation period of just 2 to 3 weeks (Norcross et al. 2001). Phenological plasticity in surfbirds and other shorebirds is not well understood, especially as it relates to timing of migratory stopovers. Potential responses to changes in the timing of stopover food availability include shifts in the timing of migration by entire species, broadening of the range of migration dates within species, and changes in bird abundance due to changes in migratory stopover food. Any shift or variability in herring spawning dates could lead to variability in the areas used by surfbirds during migratory stopover and in the timing of stopovers, reducing peak numbers.

Red-necked phalaropes are Holarctic breeders with populations that nest on the Copper River Delta (Brown et al. 2001). The breeding status of these birds makes them stand out among shorebirds in the region. These shorebirds use marine areas during migration and staging, and freshwater ponds of the Delta during breeding. There is no clear estimate of the population that breeds on the Delta but a majority of ponds have at least one and up to 10 pairs breeding on the pond shores. The birds feed on freshwater invertebrates immediately prior to, and during the breeding season. Freshwater invertebrates will be more sensitive to near-term increases in air temperature and changes in precipitation than marine invertebrates. Therefore, red phalaropes may be more exposed to changes in phenology of invertebrates than other shorebirds in the region.

Although Western sandpipers have a large population of an estimated 3.5 million birds, there are concerns that the species is declining (Farmer and Wiens 1999, USSCP 2004). Over a million western sandpipers use the Copper River Delta as a migratory stopover in the spring (Bishop et al. 2000). An abundance of food and secure resting habitat is critical to assist western sandpipers in reaching their breeding grounds in western Alaska. Little is known about the distribution of the Alaskan population of red knots, however it is suspected that the entire population use the Delta during migration. They use the mixed sand/mud areas of the barrier islands of the delta. While these areas may be susceptible to increases in storm intensity and frequency, it is unclear whether the spatial extent of barrier islands is likely to change substantially over time. In the 1970's, red knot numbers were estimated at approximately 40,000 on the Copper River Delta (Isleib and Kessel 1973). Currently the *C. c. roselaari* subspecies of red knot is estimated at below 20,000, which would indicate they are undergoing a significant decline.

Conclusions

The coastal ecosystem is an important part of the Chugach/Kenai assessment area and policy-makers and scientists are learning more about the potential effects of global climate change on the seascapes of the region. In particular, abiotic factors, including glacial changes and ocean acidification are likely to affect the assessment area (see Chapter 5 for more detail). Major biotic effects of climate change, including harmful algal blooms, changes to eelgrass beds, and consequences for shorebirds will change and influence other biota and users of the assessment area. However, maybe the most compelling conclusion from this chapter, one that does not arise directly from the review, is the heightened uncertainty involved in developing scenarios for seascape futures. In particular, the Chugach/Kenai region -- where substantial glacier change (see Chapter 3) influences sea level but also isostatic rebound, influences freshwater hydrology but also marine currents and chemistry -- is particularly difficult to imagine into the future. Uncertainty, a ubiquitous partner in any climate assessment (see Chapters 1 and 3), is particularly apparent for the dynamic region where land meets sea and the dearth of understanding of marine systems becomes apparent to managers of terrestrial and freshwater systems.

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Figures

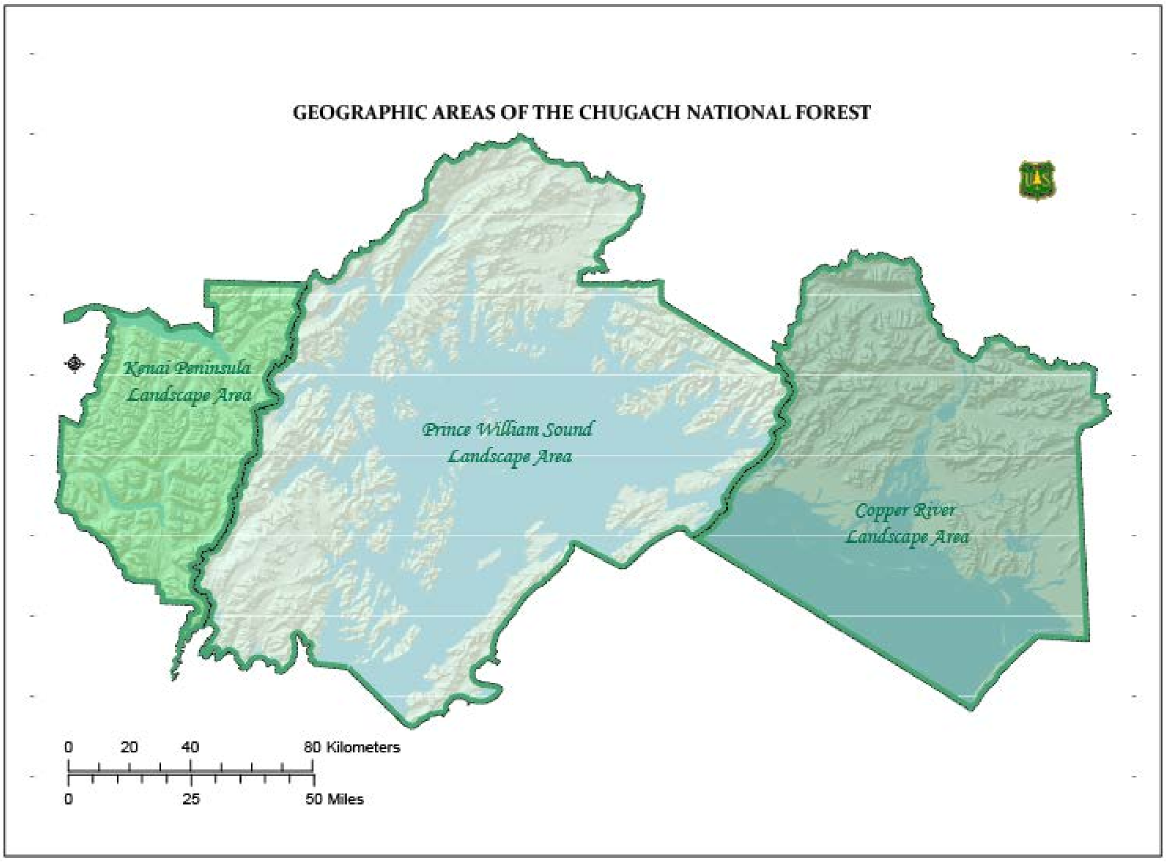

Figure 1: Geographic areas used to organize discussion of seascapes in the Chugach/Kenai assessment area.

Figure 2: Coastal dunes on Egg Island, Copper River Delta, Alaska (photo by M. Bishop)

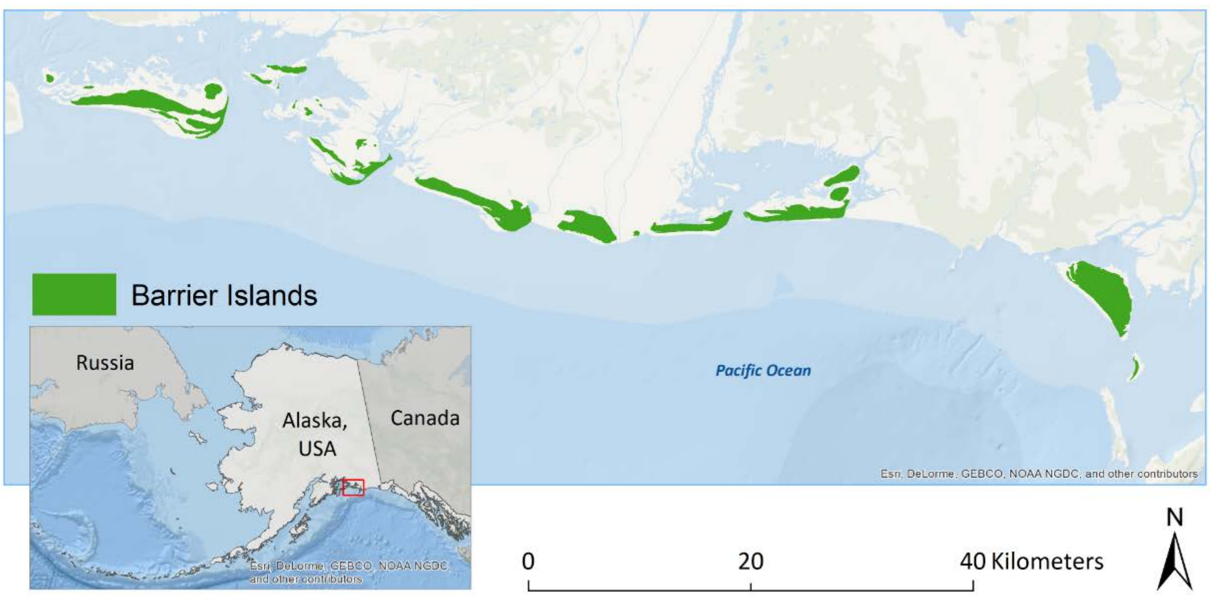

Figure 3: Distribution of barrier islands along the Copper River Delta, Alaska.

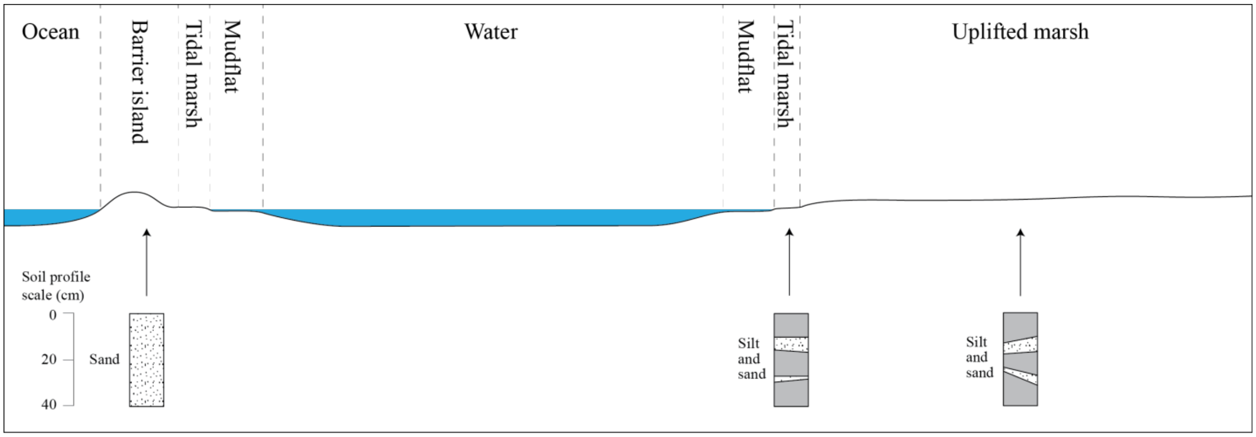

Figure 4: Schematic physiography and vegetation profile of a barrier island on the Copper River Delta, Alaska.

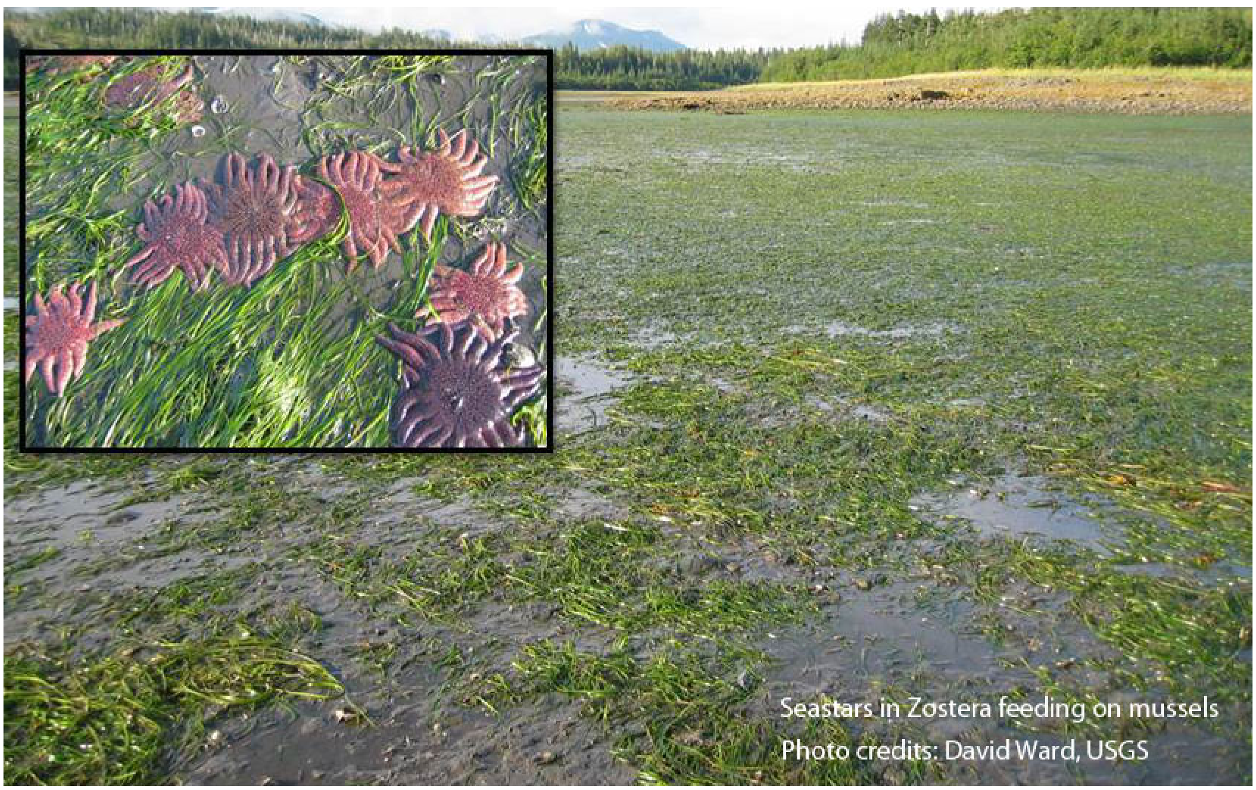

Figure 5: Seastars in *Zostera* feeding on mussels (Photo credits: David Ward, USGS).