Climate Change and the Chugach and Tongass National Forests

ABOUT DEFENDERS OF WILDLIFE

Defenders of Wildlife is a national, nonprofit membership organization dedicated to the protection of all native wild animals and plants in their natural communities. America's national forests are strongholds for much of our native flora and fauna, including one in three threatened and endangered species and more than 3,500 other imperiled species. Through our Forests for Wildlife Initiative, Defenders is working to ensure that at-risk and climate-change vulnerable wildlife and habitat persist on national forest lands as required under new national forest regulations. We are participating in the development of precedent-setting conservation plans on the Tongass and Chugach national forests and other "early adopters" of the new regulations.

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Chugach and Tongass National Forests Climate Science Synthesis

The goal of this document is to synthesize the key findings on important topics for management of national forest lands in Alaska, as detailed in climate science and vulnerability assessments published through January 2014. The synthesis brings together the results of multiple assessments so that they can be easily compared and contrasted. It begins with an overview of the reviewed documents and provides key findings and identified gaps on the following topics: snow and ice, marine and coastal ecosystems, terrestrial vegetation, freshwater systems and wildlife.

Citations for Chugach and Tongass National Forests Climate Science Synthesis

Statewide Climate Change Impacts

Report A: The United States National Climate Assessment- Alaska Technical Regional Report[1]

Markon, C.J., S.F. Trainor, and F.S. Chapin III (eds.) 2012. The United States National Climate Assessment— Alaska Technical Regional Report. U.S. Geological Survey Circular 1379. 148 pp.

This document is one of eight regional reports that provided input to the 2013 National Climate Assessment. This Alaska Technical Regional Report looks at current changes and synthesizes relevant new science and information since publication of the first Alaska regional report in 1999[2]. This report contains the most up-to-date information on statewide climate trends. The Technical Report provides outlooks and projections of climate-related conditions like temperature, precipitation, snow cover, growing season and permafrost extent. This report provides information intended to help policymakers, land managers and the general public become more informed about the current and potential effects of climate change in Alaska.

Report B: Alaska. Ch.22 In: Climate Change Impacts in the United States: The Third National Climate Assessment

Chapin, F.S., III, S.F. Trainor, P. Cochran, H. Huntington, C. Markon, M. McCammon, A.D. McGuire and M. Serreze. 2014. pp. 514-536 IN J.M. Melillo, T.C. Richmond, and G. Yohe, eds. The Third National Climate Assessment. U.S. Global Change Research Program. doi:10.7930/J00Z7150.

[1] All hyperlinks within this document were accessed on 3 September 2014.

[2] Weller, G., Anderson, P., and Wang, B. 1999. The Potential Consequences of Climate Variability and Change: Alaska. A Report of the Alaska Regional Assessment Group prepared for the U.S. Global Change Research Program. Center for Global Change and Arctic System Research University of Alaska Fairbanks.

This report is the Alaska chapter of the Congressionally mandated, multi-agency Third National Climate Assessment, released in May 2014, and is a summary of the information in Report A. The chapter, which summarizes the most important climate impacts across the state, focuses on: 1) loss of sea ice, 2) glacier melt, 3) thawing permafrost, 4) ocean warming and acidification and 5) impacts to Native Alaskans.

Impacts to Terrestrial Systems (Chronological)

Report C: Climate Change: Anticipated Effects on Ecosystem Services and Potential Actions by the Alaska Region, U.S. Forest Service

Haufler, J.B., C.A. Mehl, and S. Yeats. 2010. Climate change: Anticipated Effects on Ecosystem Services and Potential Actions by the Alaska Region, U.S. Forest Service. Ecosystem Management Research Institute, Seeley Lake, Montana, USA. 53 pp.

This report identifies potential changes that may occur according to climate change projections in southern Alaska. The report examines a broad array of resources that are managed on National Forest System lands, from yellow-cedar to tidewater glaciers. Because the report was written in 2009/2010, it relies primarily on climate projections created by Scenarios Network for Alaska and Arctic Planning (SNAP) in 2008. It additionally presents information about on-going collaborative efforts directed at climate change with suggestions for some possible responses that the Alaska region could take to address this challenge. While climate change impacts to the Chugach and Tongass National Forests are the specific focus in this synthesis, there is also a section that discusses state and private forestry and its role in assisting with climate change impacts on forests at the state level.

Report D: Evidence and Implications of Recent and Projected Climate Change in Alaska's Forest Ecosystems

Wolken, J. M., et al. [21 additional authors]. 2011. Evidence and implications of recent and projected climate change in Alaska's forest ecosystems. Ecosphere 2(11):1-35 (Article 124).

According to the Abstract, this paper represents "the first comprehensive synthesis of climate-change impacts on all forested ecosystems of Alaska, highlighting changes in the most critical biophysical factors of each region." The authors developed a conceptual framework synthesizing climate drivers and likely outcomes, which allowed them to identify the most important "biophysical factor" driving ecosystem change within each region: wildfire in interior boreal region, insect outbreaks in the south-central and Kenai boreal regions, and changes in snow and ice in the coastal temperate region. Ecosystem implications of these changes also vary by region: the interior boreal region is projected to experience a shift to more deciduous forest, the south-central/Kenai region an increased presence of invasive plants and the coastal temperate region changes in productivity.

Report E: Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the U.S. Forest Sector

Vose, J. M., D.L. Peterson, and T. Patel-Weynand (eds.) 2012. Effects of Climatic Variability and Change on Forest Ecosystems: a Comprehensive Science Synthesis for the U.S. forest Sector. Gen. Tech. Rep. PNW-GTR-870. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 265 pp.

This report is a scientific assessment of the current conditions and predicted condition of forest resources throughout the United States relative to climate change. It serves as the U.S. Forest Service technical report for the National Climate Assessment. It includes descriptions of key regional issues and examples of a risk-based assessment for climate change effects. The report includes a regional evaluation of Alaska's National Forests.

Report F: Climate Change Impact Assessment for Surface Transportation in the Pacific Northwest and Alaska

MacArthur, J., P. Mote, J. Ideker, M. Figliozzi, and M. Lee. 2012 (January). Climate Change Impact Assessment for Surface Transportation in the Pacific Northwest and Alaska. Region X Northwest Transportation Consortium. OTREC-RR-12-01. 272 pp.

This report serves as a preliminary vulnerability assessment of the effects of climate change on the surface transportation infrastructure system in the Pacific Northwest and Alaska region. The report synthesizes the region's climate data. It also identifies potential impacts on the regional transportation system, critical infrastructure vulnerable to climate change impacts, and provides recommendations for more detailed analysis and research needs as appropriate to support managing risks and opportunities to adapt multimodal surface transportation infrastructure to climate change impacts. "Transportation professionals and policy makers can use the results of this report to build a breadth of knowledge and information on regional climate change impacts, understanding vulnerabilities of the transportation system and begin creating more quantitative risk assessment models" (pg. 3).

Report G: Climate Change Effects and Adaptation Approaches for Terrestrial Ecosystems, Habitats and Species. A Compilation of the Scientific Literature for the North Pacific Landscape Conservation Cooperative Region

Tillmann, P. and P. Glick. 2013 (December). Climate Change Effects and Adaptation Approaches for Terrestrial Ecosystems, Habitats and Species: A Compilation of the Scientific Literature for the North Pacific Landscape Conservation Cooperative Region. Funded by the North Pacific LCC. 417 pp.

This report provides an explanation of what is understood about the effects of climate change on terrestrial ecosystems in the geographic region of the North Pacific Landscape Conservation Cooperative (NPLCC). Information in this report focuses on the NPLCC region, which extends from Kenai Peninsula in south-central Alaska to Bodega Bay in northern California west of the Cascade Mountain Range and Coast Mountains. The report covers 1) carbon dioxide, temperature and precipitation trends, 2) impacts on terrestrial environments, 3) implications for ecological processes, 4) implications for habitats, 5) implications for populations and communities, 6) implications for key species, and 7) adaptation options.

Impacts to Aquatic and Marine Systems (Chronological)

Report H: Global Climate Change and Potential Effects on Pacific Salmonids in Freshwater Ecosystems of Southeast Alaska

Bryant, M.D. 2009. Global climate change and potential effects on Pacific salmonids in freshwater ecosystems of southeast Alaska. Climatic Change 95:169-193. [DOI 10.1007/s10584-008-9530-x]

This assessment examines potential responses of the five species of Pacific salmon found in southeast Alaska to climate change. The focus is on the freshwater phase of the life cycle of each species and potential effect of climate change. The three major climate change variables are temperature, precipitation, and sea level. The purpose of this assessment is to identify potential effects and responses by each species, and to propose questions that can be used to quantitatively evaluate some of the effects and responses. The emphasis of the assessment and examples of potential effects are drawn from Pacific salmon stocks in southeast Alaska, but the findings may apply to salmon stocks throughout their range. This document has been cited by several other assessments that we reviewed and appears to provide the foundation for most broad evaluations of salmon response to climate change in the region.

Report I: Assessing the Vulnerability of Alaska's Coastal Habitats to Accelerating Sea-level Rise Using the SLAMM Model: A Case Study for Cook Inlet

Glick, P., J. Clough, and B. Nunley. 2010. Assessing the Vulnerability of Alaska's Coastal Habitats to Accelerating Sea-level Rise Using the SLAMM Model: A Case Study for Cook Inlet. National Wildlife Federation. 17 pp.

This report includes a detailed account of the application of the Sea Level Affecting Marshes Model (SLAMM) in the Cook Inlet region. Also included is a white paper that provides an overview of Alaska data gaps and challenges to applying SLAMM in Alaska and suggestions for preliminary steps that should be taken to apply SLAMM with maximum effectiveness across the state. This report primarily highlights the need for further research and monitoring for climate related changes in Alaska's coastal areas.

Report J: Climate Change Effects and Adaptation Approaches in Freshwater Aquatic and Riparian Ecosystems in the North Pacific Landscape Conservation Cooperative

Tillmann, P. and D. Siemann. 2011 (December). Climate Change Effects and Adaptation Approaches in Freshwater Aquatic and Riparian Ecosystems of the North Pacific Landscape Conservation Cooperative Region: A Compilation of Scientific Literature. Final Report. National Wildlife Federation – Pacific Region, Seattle, WA. 268 pp.

This report provides an explanation of what is understood about the effects of climate change on freshwater ecosystems in the geographic region of the North Pacific Landscape Conservation Cooperative (NPLCC). Information in this report focuses on the NPLCC region, which extends from Kenai Peninsula in south-central Alaska to Bodega Bay in northern California west of the Cascade Mountain Range and Coast Mountains. The report covers 1) carbon dioxide, temperature and precipitation trends, 2) major hydrologic impacts, 3) implications for freshwater ecosystems, 4) implications for species, populations and communities, 6) implications for key species, and 7) adaptation options.

Report K: Climate Change Effects and Adaptation Approaches in Marine and Coastal Ecosystems of the North Pacific Landscape Conservation Cooperative Region

Tillmann, P. and D. Siemann. 2011 (December). Climate Change Effects and Adaptation Approaches in Marine and Coastal Ecosystems of the North Pacific Landscape Conservation Cooperative Region: A Compilation of Scientific Literature. Funded by the U.S. Fish and Wildlife Service Region 1 Science Applications Program. 264 pp.

This report provides an explanation of what is understood about the effects of climate change on marine and coastal ecosystems in the geographic region of the North Pacific Landscape Conservation Cooperative (NPLCC). Information in this report focuses on the NPLCC region, which extends from Kenai Peninsula in south-central Alaska to Bodega Bay in northern California west of the Cascade Mountain Range and Coast Mountains. The report covers 1) carbon dioxide, temperature and precipitation trends, 2) impacts on marine and coastal environments, 3) implications for coastal nearshore habitats and ecosystems, 4) implications for populations and communities, 5) implications for key species, and 6) adaptation options.

Key Findings

Climate Changes

- Temperatures in southeastern and south-central Alaska have risen by an average of 3 to 4°F from the middle of the 20th century to the early 21st century, with winter temperatures showing the largest increase (Reports A, B, C, G, J, K).
- While the various reports (Reports A, B, C, G, J, K) frame scenarios and timeframes somewhat differently, they generally agree that the region will see increases of about 2°F over the next few decades, 3-4°F in the second half of this century, and 4-7°F by late century.
- Where precipitation trends are discussed, it is generally agreed that both total precipitation and incidence of heavy precipitation have increased, and will continue to do so; however the roughly 10% projected increase will be more than offset by increased evaporation from soil and plants due to warmer temperatures, leading to drier conditions (Reports A, C, G, J, K).

Snow and Ice

- A likely reduction in the proportion of precipitation falling as snow, combined with conditions favorable for more rapid melting, will reduce snowpack, leading to stream flow increases in spring and decreases in summer and fall (Reports C, D, F, J).
- Most of the glaciers in the region are experiencing accelerated melting, with the most pronounced effects at low elevations. The resultant changes in flow and sediment output have multiple implications for river and coastal ecosystems (Reports A, B, C, D, J, K).

Terrestrial Habitats

- Key projected terrestrial impacts include decreases in soil moisture (Reports B, C, G), a longer growing season (Report G), increased frequency and size of forest fires (Reports B, G), continued worsening of outbreaks of spruce beetles and other forest pests (Report G), and establishment of invasive plants (Reports E, G, K).
- Multiple biome shifts are underway or expected, including species range shifts (Reports C, G), declines in key tree species (Reports E, G), and shrinking of alpine habitats due to encroachment of shrubs and trees (Report G).

Freshwater Habitats

- Lakes, ponds and wetlands are susceptible to drying out, with many of these habitats already showing decreases in area (Reports B, C, J).
- Rivers and streams are expected to see alterations in stream flow amount and timing, temperature and nutrient content due to changing precipitation and melting patterns, with effects on benthic, aquatic plant and fish communities (Reports J, K).

Coastal and Marine Habitats

- Projections of sea-level rise, which would have consequences for coastal ecosystems that are important to shellfish and migratory birds, vary widely between reports and even among locations within reports, due to the complexities of local uplift from glacial melting and seismic activity (Reports A, C, D, I, K).
- Figures vary slightly, but Reports B, C, and K generally agree that the oceans have become about 30% more acidic and that the consequences of continued acidification for marine food webs would be severe.
- Reports C and K agree that the dynamics of ocean temperature, changes in upwelling patterns, nutrient circulation and oxygen concentration are poorly understood, but that a warming climate could affect ocean productivity by altering these processes and in turn, impact marine wildlife.

Wildlife

- Potential impacts to trout and salmon species include changes in life cycle timing, reduced food availability, loss of thermal refuge and degradation of spawning habitat (Reports B, H, J, K).
- Birds associated with tundra (white-tailed ptarmigan) and glaciers (Kittlitz's murrelet) may be most at risk from climate change, but shorebirds, waterfowl, seabirds and forest birds may also see changes to habitat quality and food availability (Reports B, G, K).
- The response of the area's mammals to climate change does not show clear trends, with some species benefiting and others declining (Reports B, G).

Compendium of Findings

Climate Changes

- Temperature. The various reports generally agree on both observed and projected increases in temperature, but vary in the time frame, season and location being compared. Table 1 and Table 2 summarize the findings of several reports for observed and projected temperatures, respectively. A text summary follows the tables.

Report	Time frame	Location	Winter	Spring	Summer	Autumn	Annual	Data Source
A	1949-2005	Statewide	6.3°F	4.1°F	2.3°F	1.4°F	"nearly 4°F"	Stafford et al, 2000; Shulski & Wendler, 2007
B	1949-2011	Anchorage (Chugach)	5.8 °F	3.5 °F	1.4 °F	1.7 °F	3.2 °F	Stewart et al. 2013
B	1949-2011	Juneau (Tongass)	6.4 °F	2.9 °F	2.0 °F	1.3 °F	2.1°F	Stewart et al. 2013
C	1971-2008	Statewide					2.69°F	SNAP 2008
C	1958-2008	Statewide	6.3°F				3.4°F	USGCRP 2009
C	1971-2008	Juneau (Tongass)					3.5°F	SNAP 2008
G, J, K	1949-2009	Juneau (Tongass)					3.2°F	AK Climate Research Ctr website, 2009
G, J, K	1971-2000	Anchorage (Chugach)					2.26°F	Alaska Ctr. for Climate Assessment & Policy, 2009

Table 1. Observed temperature change as documented by various reports.

Report	Baseline	Region	Season	Early	Mid	Late	Data Source
A, B	1971-2000	SE/SC	Annual	1.5-2.5°F (2021-2050)	2.5-3.5°F (2041-2070)	3.5-4.5°F (2070-2099)	CMIP3-15, **B1** (Low emissions)*
A, B	1971-2000	SE/SC	Annual	1.5-2.5°F (2021-2050)	2.5-4.5°F (2041-2070)	5.5-7.5°F (2070-2099)	CMIP3-15, **A2** (High emissions)*
C	2009	SC	Summer	Fine scale map; refer to figure A-3, page 44 for temperature projections in 2039, 2069, 2099			SNAP 2009, **A1B** (Middle Emissions)
C	2009	SC	Winter	Fine scale map; refer to figure A-5, page 46 for temperature projections in 2039, 2069, 2099			SNAP 2009, **A1B** (Middle Emissions)
C	2009	SE	Summer	Fine scale map; refer to figure A-8, page 49 for temperature projections in 2039, 2069, 2099			SNAP 2009, **A1B** (Middle Emissions)
C	2009	SE	Winter	Fine scale map; refer to figure A-10, page 51 for temperature projections in 2039, 2069, 2099			SNAP 2009, **A1B** (Middle Emissions)
G, J, K	1960s-1970s	State-wide	Annual	2.0- 4.0°F (2020)	3.5-6°F (2050)	5-8°F (2090)	CMIP3-A, **B1** (Karl et. al. 2009)
G, J, K	1960s-1970s	State-wide	Annual	2.0- 4.0°F (2020)	4-7°F (2050)	8-13°F (2090)	CMIP3-A, **A2** (Karl et. al. 2009)

Table 2. Projected temperature increase as documented by various reports.

- Text references for temperature information:
  - Report A says, "The most recent, comprehensive and statistically rigorous analyses of Alaska's climate records indicate that average annual statewide temperatures have increased by nearly 4°F over the period 1949-2005" (pg. 11).
  - Report A provides a seasonal breakdown of statewide average observed temperature increases: 6.3°F in winter, 4.1°F in spring, 2.3°F in summer, and 1.4°F in autumn (pg. 11). Report A provides regional temperature trend information for some parts of the state, but not for the southeast and south-central areas.
  - Report A maps projected temperature increase (pg. 15) based on 15 simulations of the Coupled Model Intercomparison Project Phase 3 (CMIP3), compared to the period 1971-2000 and shows the following for south-central and southeast Alaska:
    - For 2021-2050, 1.5-2.5°F under both the lower (B1) and higher (A2) emissions scenarios
    - For 2041-2070, 2.5-3.5°F under B1 and 2.5-4.5°F under A2
    - For 2070-2099, 3.5-4.5°F under B1 and 5.5-7.5°F under A2

        - Report A also contains detailed projections on monthly temperature change, changes in freeze dates and other information and should be referred to directly for specific forecasts.
    - Report B states that the average Alaska temperature has increased by 3°F over the past 60 years, with winters warming by 6°F. The state has seen more very hot days and fewer very cold days (pg. 516).
    - Report B, as summary document, shows the same maps as Report A, but also averages the data from Report A and projects that statewide average annual temperatures will rise by a further 2°F to 4°F by 2050. By the end of the century, temperatures in the southern part of the state are projected to rise by 4 to 6°F under a low emissions scenario and 6°F to 8°F under a higher emissions scenario (pg. 516).
    - Report C includes 2008 data from Scenarios Network for Alaska and Arctic Planning (SNAP) stating that Alaska has seen a statewide increase in temperatures of 2.69 degrees Fahrenheit since 1971.
        - Juneau was reported to have an increase of 3.54 F; Valdez was reported to have an increase in temperature of 3.76°F and Yakutat an increase of 2.75°F (Pg. 7).
    - Report C includes models for south-central and southeast Alaska created by SNAP using A1B Emissions Scenarios. The results are mapped at a fine spatial scale rather than expressed numerically:
        - Growing season length is predicted to increase substantially over the next 100 years in both the south-central (Figure A-1) and southeast (Figure A-6) Landscapes. *See Appendix A of Report C for figures.*
        - Summer temperatures are expected to rise in both landscapes (Figures A-3 and A-8).
        - Winter temperatures are also expected to increase in both landscapes (Figures A-5 and A-10).
        - Using these models the general predicted effects of climate change on precipitation in these regions are (Pg.8):
            - Temperatures will increase, with winter temperatures increasing at a higher rate than summer temperatures
            - Length of growing seasons and frost free days will increase
            - Temperatures in seasonal transition months in many locations will shift from below freezing to above freezing.
    - Report E explains that wildfire, invasive species and warmer temperatures have contributed to recent spruce beetle outbreaks in south-central Alaska by reducing the beetle life cycle from two years to one year (pg. 206).
    - Report G (pg. 12), Report J (pg. 5), and Report K (pg. 5), citing the National Climatic Data Center, find that average annual temperature has increased 3.4°F (~1.9°C) in Alaska from 1949 to 2009, and that average winter temperature in Juneau has increased by +6.2°F (+3.4°C) during the 20th century. Report K adds that

in Juneau, spring temperatures have increased by 2.9°F (1.6°C) and autumn temperatures by 1.4°F (0.8°C) (pg. 11).

- Report G (pg. 16), Report J (pg. 16), and Report K (pg. 6, 17), citing Karl et al. 2009[3], project that
  - "By 2020, compared to a 1960-1970s baseline, average annual temperatures in Alaska are projected to rise 2.0°F to 4.0°F (1.1-2.2°C) under both the low-emissions B1 scenarios and higher-emissions A2 scenario."
  - "By 2050, average annual temperatures in Alaska are projected to rise 3.5°F to 6°F (1.9-3.3°C) under the B1 scenario, and 4°F to 7°F (2.2-3.9°C) under the A2 scenario (1960-1970s baseline). Later in the century, increases of 5°F to 8°F (2.8-4.4°C) are projected under the B1 scenario, and increases of 8°F to 13°F (4.4-7.2°C) are projected under the A2 scenario (1960-1970s baseline)."

- Precipitation
  - Report A mentions that much of southern and southeastern Alaska have experienced 20% increases in wintertime precipitation (December-February) over the period 1949-2005, but one station in the southeast tip of the state (Annette) showed a 24% decrease over this time period (pg. 12).
  - Report A finds that many weather recording stations in southeast and south-central Alaska have shown "upward trends in occurrence of extreme three-day precipitation events from 1950 to 2008," but cautions that these trends have mostly not statistically significant (pg. 13).
  - Report A maps projected precipitation increase (pg. 27) based on 15 simulations of the Coupled Model Intercomparison Project Phase 3 (CMIP3), compared to the period 1971-2000 and shows the following for south-central and southeast Alaska:
    - For 2021-2050, 5-10% under both the lower (B1) and higher (A2) emissions scenarios
    - For 2041-2070, 5-10% under B1 and 5-15% under A2
    - For 2070-2099, 10-15% under B1 and 15-20% under A2
    - Report A also contains detailed projections on monthly and seasonal precipitation change and should be referred to directly for specific forecasts.
  - Report B does not specify precipitation projections for Southern Alaska, other than to say that precipitation is expected to increase, but not enough to offset evaporation from warmer temperatures (pg. 516).
  - Report C provides the U.S. Global Change Research Program statistic that the average snow free days have increased across Alaska by an average of 10 days (Pg. 7).

[3] Karl, T.R., J.M. Melillo, and T. C. Peterson (eds.). 2009. Global Climate Change Impacts in the United States. <Projections superseded by the Third National Climate Assessment, See Report A and Report B in this document.>

- Report C includes models for south-central and southeast Alaska created by SNAP using A1B Emissions Scenarios:
  - Winter precipitation levels are expected to increase in both landscapes (Figures A-4 and A-9).
  - Summer precipitation is expected to rise in both landscapes (Figures A-2 and A-7).
  - Using these models the general predicted effects of climate change on precipitation in these landscapes are (pg. 8):
    - Precipitation will increase
    - More precipitation will fall as rain rather than snow
    - Evapotranspiration rates will increase
    - P-PET ratios (which display the rate of evapotranspiration)will decrease in summer, causing dryer conditions in summer for many locations
    - Storm intensities will increase
- Report E points out that because southeast Alaska has historically had an average winter temperature of 32°F and long growing seasons, even a small average temperature increase could strongly increase rain and decrease snowpack.
- Report G, citing the National Weather Service, finds precipitation has increased in both warm and cold seasons in Juneau, and that the growing season has lengthened by one day 1971-2000 vs. 1981-2010) (pg. 21). Report K, same (pg. 21).
- Report G projects that precipitation will increase in southeast and south-central Alaska, but that warmer air temperatures will offset the increase and lead to a decrease in soil moisture (pg. 24). Report J (pg. 24) and Report K (pg. 25) cite the same information. Report G notes that web-based mapping tools for precipitation are available from University of Alaska-Fairbanks (pg. 25) [update: web link is http://www.snap.uaf.edu/maps.php].
- Report G (pg. 21), Report J (pg. 5, 20), and Report K (pg. 5) find that in southeast Alaska from 1949 to 1998, mean total annual precipitation was at least 39 inches (1000 mm), with a maximum of 219 inches (5577 mm) at the Little Port Walter station, and that in south-central Alaska from 1949 to 1998, mean total annual precipitation was 32 inches (800 mm) to 39 inches (1000 mm).

Snow and Ice

- ### Snowpack/line
  - Report C predicts that in some drainages, there will be changes in the timing of run-off as snow packs move higher, and snowmelt occurs earlier in the spring (Pg. 12).

- Report D found that during the winter, ecosystems that had deep snowpacks lose more carbon than those with shallow snowpacks in south-central and southeast Alaska (pg. 12).
- Report F warns that the projected decrease in snowpack could lead to a decrease in available surface water resources during the summer (pg. 39).
- Report J states that there has been a decrease in snowfall and snowpack, particularly at lower and mid elevations (Pg. ii).
    - In Juneau winter snowfall decreased by about 15%, or nearly 1.5 feet between 1943 and 2005 (Pg. ii).
    - Between 1948 and 2002, the timing of peak spring streamflow has shifted ten days earlier (pg. 34). A further ten- to twenty- day earlier shift is projected by 2100 (pg. 42).
- Report J states "Increases in winter precipitation could lead to increased snowpack, however, winter melting events and a shortening of the period of snow accumulation could have the opposite effect" (pg. 43).
- Report J indicates that models show strong agreement that runoff will increase by 20 to 40% over this century due to earlier snow melt and a higher proportion of precipitation falling as rain (pg. 43-4). These trends are also projected to lead to reduce stream flow in the summer and autumn (pg. 44).

- Glaciers
    - Report A states that in all of Alaska, the majority of glacial loss is concentrated in the Gulf of Alaska region which is primarily encompassed by the Chugach and Tongass National Forests.
        - The basin-averaged thinning rates in Alaska's St. Elias Range are 50 times greater than basin-averaged thinning rates in Greenland- another area of the world demonstrating large scale glacial recession (pg. 45).
    - Report B states that "most glaciers in Alaska and British Columbia are shrinking substantially. This trend is expected to continue and has implications for hydropower production, ocean circulation patterns, fisheries, and global sea level rise" (pg. 515).
    - Report B says that glacial ice loss in Alaska and British Columbia is among the fastest on Earth, and is currently contributing "20% to 30% as much surplus water to the oceans as does the Greenland Ice sheet - about 40 to 70 gigatons per year," the equivalent of 10% of the flow of the Mississippi River (pg. 519).
        - Glacial melting is projected to continue through this century, and notes that "glaciers continue to respond to climate warming for years to decades after warming ceases" (pg. 519).
        - Increased glacial melt may increase hydropower potential in the short run but decrease it in the long run (pg. 519).
        - Glacial melt is an important input of many limiting nutrients for ocean productivity, including "organic carbon, phosphorus, and iron" (pg. 519).

- Report C discusses the considerable risk tidewater glaciers face due to climate change and impact on the loss of that habitat type for certain specialized species like Kittlitz's murrelet (pg. 17). This species is experiencing an annual decline rate of 18% thought to be linked to climate change from loss of tidewater glacier habitat around Prince William Sound (pg. 17).
- Report C states that the Tongass and Chugach National Forests are key places to educate people about climate change effects through the compelling images of tidewater glacier recession (pg. 30).
- Report D notes that currently about 47% of water discharged into the Gulf of Alaska originates from glaciers and ice fields (pg. 16).
  - "The loss of glacial inputs and changes in the timing of surface runoff associated with changes in the snowpack and snow/rain ratios are expected to impact stream habitats and the annual pattern of carbon and nutrient inputs to the freshwater and marine systems" (pg. 16).
  - Report K cites the same information, and adds that 10% of this discharge comes from glacial retreat and mass loss (pg. 50-1).
- Report J discusses both the historically observed trends for glacial change in Alaska and the future projections (pg. 50).
  - From the mid-1950s to the mid-1990s, volume losses from 67 of Alaska's glaciers were more than double the estimated annual losses from the entire Greenland Ice Sheet over the same time period (pg. 50).
  - Alaska's tidewater glaciers will grow more unstable, with increased calving and subsequent melting (pg. 50).
  - The effect of glacial ice loss is particularly evident at low elevations, where many glaciers are retreating at a rate of 2-3 meters (up to 10 feet) per year (pg. 53).
  - In the west arm of Glacier Bay near Juneau, the glaciers have retreated 60 miles and are a mile thinner (pg. 53). However, a small number of glaciers are advancing (pg. 54).
- Report K states: "Neal et al.'s (2010) results indicate the region of the Gulf of Alaska from Prince William Sound to the east, where glacier runoff contributes 371 km^3 per year, is vulnerable to future changes in freshwater discharge as a result of glacier thinning and recession" (pg. 51).

Terrestrial Ecosystems

- Hydrology
  - Report B projects that expected precipitation increase will not be sufficient to offset evaporation from warmer temperatures (pg. 516).

- Report C states based on modeling that P-PET ratios (which display the rate of evapotranspiration) will decrease in summer, causing dryer conditions in summer for many locations (pg. 8).
- Report G finds that the increase in potential evapotranspiration has exceeded the increase in precipitation, leading to soil moisture deficit (pg. 31), and projects that this trend will continue, except in the highest elevation regions (pg. 35).

- Nutrient Cycling
  - Report G discusses carbon stocks in Alaska's forest vegetation, soils and peatlands, as well as dissolved organic carbon, nitrogen and productivity. The Tongass National Forest, for example, contains 7.7% of U.S. forest carbon stocks (p. 132-3). Models differ on the question of whether carbon loss due to increased fire will exceed carbon gained due to longer growing season over the next 75 years, but agree that Alaska will be a carbon source by the end of the 21st century (pp. 139).
- Growing Season
  - Report G finds that the growing season has lengthened by 1.51 days per decade in Talkeetna (between Chugach National Forest and Denali National Park) and 6.97 days per decade in Yakutat (near the Tongass National Forest) from 1949 to 1997 (pg. 41).
  - Report G projects that growing season will increase by 10-20 days by 2050, and 20-40 days by 2100, with coastal regions seeing the higher-end estimates [*Projections from SNAP are compared to 1961-1990 climate normals (downscaled using PRISM to 2 km resolution) using the five best-performing GCMs of the fifteen used in the IPCC AR4 and run under the A1B scenario]* (pg. 43).
- Fire
  - Report B projects that the "annual area burned in Alaska is projected to double by mid-century and triple by the end of the century" with possible changes in forest composition following from this (however these projections are not specific to southern Alaska) (pg. 521).
  - Report G finds that observed mean fire return interval in white and Lutz spruce is 400-600 years (range 90-1500 years). Historically, spruce beetle outbreaks in these communities occur about every 50 years, indicating that there is not necessarily a correlation between beetle outbreaks and increased fire risk. However, this may be changing due to warmer summers, increased human presence, and the unusually large acreage of the current beetle outbreak (>1 million acres on Kenai Peninsula alone) (pp. 54-5).
  - Report G projects (using MC1 dynamic global vegetation model) 17%–39% increase in burn area in south-central Alaska in 2050-2100 compared to 1950-2000, due to encroachment of temperate forests into tundra regions, and suggests that warmer summers and an increase in lightning will cause fire to become a "major disturbance" in the hemlock and spruce rainforests of southeast Alaska (pg.69).

- Pests and Pathogens
  - Report D warns that warmer temperatures were an important factor in the spruce beetle outbreaks from 1971-1996 in the Kenai boreal forest (pg. 16).
  - Report G observes that spruce beetle outbreaks have historically been the most important form of natural disturbance on the Kenai Peninsula (pg. 88). Evidence suggests historic outbreaks are associated with cool-phase Pacific Decadal Oscillation conditions and tended to follow an El Nino (warm-phase ENSO) with warm summer conditions and late summer drought: when the 5-year average summer temperature reached 50.5 °F (10.3 °C), the outbreak probability reached 50% (pg. 89, 91).
    - 3.7 million acres in Alaska have been affected by spruce beetle outbreaks since 1989, with the Kenai Peninsula sustaining the heaviest losses: 80% mortality in the 1990s, "the largest tree die-off ever recorded in North America" (pg. 90).
    - Report G describes the severity of the recent known outbreaks: 1810s was "low," 1870s, 1910s and 1970s were "moderate-high", and 1990s was "particularly high" (pg. 90). Future infestation may be endemic rather than episodic, attacking trees as soon as they reach appropriate size (p. 106).
    - Spruce budworm moths have been able to reduce their life cycle from two seasons to one due to longer growing season (pg. 91).
    - Sitka spruce aphid outbreaks have increased since the 1970, probably due to warmer winters (p. 91) and projects that the aphids range will expand (pg. 106).
    - Outbreaks of cytospora canker are affecting alder species (thinleaf, green, and Sitka) in Alaska (p.91).
    - Climate changes will also likely favor expansion of hemlock dwarf mistletoe (p. 91).
    - Mountain pine beetle could expand its range into Alaska, with lodgepole pine and shore pine potentially affected (pg. 106).
    - Western balsam bark beetle expands its elevational range 30 meters per 1°C warming (pg. 106).

- Windthrow and Other Disturbance
  - Report G observes that windthrow is an important form of disturbance within Alaska's forests, with blowdowns ranging from 1 to 1,000 acres, but usually around 50 acres in size (pg. 117). The expected increase in severe weather events could increase the incidence of large windthrows, as well as the risk of landslides due to heavy precipitation (pg. 123).
  - Report G suggests that isostatic rebound due to glacial melting could increase the frequency of earthquakes in the region (pg. 122).

- Vegetation
  - Report C discusses the upward expansion of forest ecosystems that tend to occur with increases in temperature and precipitation (pg. 17).
    - A 3°F increase in temperature is typically associated with a 1000-foot gain in elevation which could push forest ecosystems in south-central and southeast up 2000-3000 feet in the next hundred years depending on the actual average temperature increase (pg. 17).
    - This shift could lead to a substantial decrease in alpine or tundra vegetation types (pg. 18).
    - Furthermore, decreases in avalanche falls and formation sizes, from decreases in snowpack, could allow trees to grow in areas previously not possible due to their disturbance (pg. 18).
  - Report E discusses that in the past 100 years the Alaska yellow-cedar has declined due equally to overharvesting by humans and warmer temperatures drying them out (pg. 207).
  - Report G contains an extensive discussion of Alaska yellow-cedar decline, and notes that it is a culturally, ecologically and economically important tree in southeast Alaska. The cause of decline here (in contrast to Report E) is given as shallow root systems (an adaptation to exploit nitrate in the upper levels of wet soils) that were traditionally protected from freezing by a snow layer, which has reduced in recent years. Western redcedar, by contrast, may have a lower proportion of shallow roots and thus less prone to mortality from surface freezing. Report G projects (based on the work of Hennon et al. 2012), that western redcedar may replace yellow-cedar across lower-elevation sites south of 57°N latitude. Yellow-cedar's best chance of persistence may (paradoxically) be on well-drained soils, due to its formation of deeper root systems there; however, the report warns that active management would be needed to allow the species to compete with faster-growing western hemlock and Sitka spruce. The report finds that favorable conditions in wet soils may develop north of yellow-cedar's current range, but low reproductive capacity will impede range shift, and active translocation may be a necessity (pg. 153-156).
  - Report G discusses low-to mid- elevation forests at length:
    - It is expected that in low- to mid-elevation forests, windthrow will be an increasingly important form of disturbance on exposed sites, and fungal pathogens will be an important source of individual tree mortality and gap formation in protected sites. Trees and shrubs are likely to benefit more from warming than grasses, due to photosynthetic biochemistry differences (p.169).
    - Forested areas on the Kenai Peninsula have increased by 28% from 1950 to 1996 (pg. 178).
    - Multiple changes are anticipated in low-to mid-elevation forests, including upslope movement of Sitka spruce and western hemlock, at the expense of

        - tundra vegetation and mountain hemlock. Climate scenarios project that temperate coniferous forests will expand in Southern Alaska, at the expense of tundra and boreal forests, and that maritime coniferous forests will expand in areas where the difference between maximum and minimum mean monthly temperature remains below 59°F (pg. 189).
        - Warming and drying will likely hasten the transition of forested wetlands to non-wetland forests (pg. 190).
        - There exists the potential for multiple biome shifts within Alaska based on climate envelope modeling (but not accounting for speed of dispersal, etc. (pg. 191).
    - Report G also discusses Alpine and Subalpine Habitats:
        - From 1951 to 1996, tundra in the Kenai peninsula retreated upward about 130 feet, but replacement vegetation varied, with shrubline moving up by 190 feet, treeline by 160 feet, and timberline by 20 feet (pp. 220-1). Tundra retreated less on slopes with southern exposure than northern exposure, possibly due to inadequate moisture for tree establishment (pg. 221).
        - By the end of the 21st century, it is projected that 75-90% of the tundra that existed in southeast Alaska in 1922 will have converted to forest cover (pg. 227).
    - Report J, despite its main focus on freshwater ecosystems, includes a two-page discussion of range shifts among terrestrial biomes and potential areas of climatic refuge for each (pp. 103-105).

- Weeds and Invasive Plants
    - Report E points out that the large proportion of goods are shipped to Alaska via ports in south-central Alaska, so invasive plant species will likely become an increasingly important risk factor (pg. 206).
        - Several invasive plant species in Alaska have already spread aggressively into burned areas like the Kenai Peninsula including Siberian peashrub (*Caragana arborescens*), narrowleaf hawksbeard (*Crepis tectorum*), and white sweetclover (*Melilotus alba*) (pg. 206).
    - Report G finds that the rate of non-native plant introductions has increased from 1 to 3 taxa per year over the past 70 years (pg. 263).
        - Establishment of the following invasive weeds is expected in southeast and south-central Alaska: garlic mustard, knotweeds, orange hawkweed, whiter sweetclover, and European Mountain ash (pg. 267).
    - Report K does not list any information about marine invasive species, but notes that marsh migration inland in response to SLR could present opportunities for colonization by invasive *Spartina*, which provides less habitat value for wetland species than native marsh vegetation. *Spartina* control might be one of the keys to successful marsh transition (pg. 152).

Freshwater Ecosystems

- ### Wetlands and Peat Bogs
  - Report B mentions that average lake area has decreased over the past 50 years in parts of Alaska outside the perrmafrost zone. Due to Alaska's importance for waterfowl breeding, the drying of wetlands could have far-reaching impacts to migratory ducks and geese (pg. 520).
  - Report C notes that although the south-central and southeast models show an increase in precipitation, increased evaporation and evapotranspiration due to warming could still cause an overall drying of wetlands in these areas (pg.17).
    - This effect has already been observed on the Kenai Peninsula where over two-thirds of the water bodies were observed to have decreased in area between 1950 and 1996 (Klein et al. 2005) (pg.17).
  - Report J suggests that changes in precipitation type, timing of runoff, and summer drying may lead to more rapid succession of shallow lakes and wetlands to meadows and even to forest cover (pg. 102).
  - Report J projects the warming could shift peatlands from a carbon sink to source, due to drying and increased rates of decomposition (pg. 103).

- ### Lakes and Ponds
  - Report B observes that lakes in southern Alaska have gotten smaller due to evaporation and a longer growing season. (pg. 520)
  - Report J states that "across the southern two-thirds of Alaska, the area of closed-basin lakes (lakes without stream inputs and outputs) has decreased over the past fifty years. This is likely due to the greater evaporation and thawing of permafrost that result from warming" (pg. 94). The effect of climate change on stratification and eutrophication is identified as an information gap (pg. 93), as is effects on seasonal ice cover (pg. 98).
  - Report J projects a decline in river delta lakes due to reduced winter ice-jams (pg. 103).

- ### Rivers and Streams
  - Report J identifies several potential climate change impacts on rivers and streams, but emphasizes that more information is needed on a number of topics:
    - Streamflow and flooding dynamics in Alaska was identified as an information gap (pg. 63), but makes a generalized prediction that more winter flooding will occur (pg. 65).
    - Stream temperatures are an area of data deficiency (pg. 69), and Report J makes no specific projections beyond that of warmer streams in summer (pg. 71). Additional information gaps for Alaska include the effects of

climate change on water quality and chemistry (pg. 75) and on groundwater (pg. 80).
        - Nutrient input from the decay of salmon carcasses post-spawning is an important contributor to stream productivity (pg. 88). Therefore, warmer stream temperatures may increase productivity due to enhanced rates of decomposition (and thus availability of organic matter and nutrients); however, it is unclear if this will offset the increased demand for these nutrients due to warmer water boosting metabolic rates (pg. 90).
        - Finally, climate changes might alter the distribution and composition of freshwater invertebrate communities; however detailed information was not available (pg. 153).

    - Report J observes that invasive reed canary-grass is already established in river systems in the Kenai Peninsula and southeast Alaska, and has a large likelihood of spreading, due to warming and multiple available vectors (pg. 127-9).
    - Report J also projects that three additional aquatic invasive plants could become more widespread due to warming: hydrilla, Eurasian watermilfoil, and white water lily (pg. 129).
    - Report K indicates that precipitation type shift from snow to rain, will increase runoff and stream flows (pg. 49).
    - Report K states that "In south-central and southeast Alaska from 1948 to 2002, the timing of the center of mass of annual flow has shifted at least ten days earlier, while the timing of the spring pulse onset has shifted five to fifteen days earlier in some locations and up to five days later in others." (pg. 50)
    - Report K state that "decreasing watershed glacial coverage leads to lower riverine yields of freshwater, inorganic phosphorus, and labile dissolved organic matter" (pg. 99).

Marine and Coastal

- Sea level
    - Report A states that between the Kenai Peninsula and southeast Alaska, land that was previously weighed down by glaciers is rising slightly due to the decreased weight as they melt. This phenomenon, known as glacial isostatic adjustment, has produced uplift rates of 0.4 in/yr. or more, with the peak uplift rates exceeding 1.2 in/yr. (Pg. 42).These values are about 3 and about 10 times faster than global average mean sea-level rise (Pg. 42).
    - Report C points to estuarine ecosystems as some of the most vulnerable to sea level rise (pg. 9).
        - In the Chugach and Tongass National Forests, those with the highest ecological and economical value are the Copper River Delta, Yakutat

Forelands and Stikine River Flats. They are important stopover sites for migratory birds, provide major fish spawning habitat and critical shellfish production areas. Consequently, changes in coastal habitats as a result of sea level rise would have large potential effects (pg. 9).

- Report C also notes that sea level rise could be less of a concern due to isostatic rebound and for the Copper River Delta, still experiencing uplift after the 1964 earthquake (pg. 9).
  - "Rising sea levels may also create new estuarine areas depending on the topography of an area, so decreases in ecosystems in some areas may be offset by increases in others" (pg. 9).
- Report D projects that sea level in south-central Alaska will rise by between 8-61 cm by 2050 and 18-183 cm by 2100. These estimates are so broad because they take into account geological processes related to seismic activity and isostatic rebound and the large degree of variability that comes with the combined effects of those changes (pg. 19).
- Report I uses Sea Level Affecting Marshes Modeling (SLAMM) to determine predicted sea level change in the Anchorage/Kenai area and finds that sea level rise ranges from negative 0.7 meters to positive 1.3 meters by 2100 in that area (Pg. 16).
- Report K states that observed sea level has declined 0.674 inches per year (17.12 mm/yr) at Skagway (1944-2007) but increased 0.2268 inches per year (5.76 mm/yr) at Cordova (1964 to 2007) (pg. 66). Of eleven locations where measurements have been ongoing, only Cordova and Anchorage have had positive sea-level rise (SLR) (pg. 68).
- Report K projects that global mean SLR will be outpaced by the effects of isostatic rebound due to glacial retreat over the next century, resulting in local sea level decrease of 2.1 to3.4 feet (0.64-1.0 m) (pg. 77).

- Ocean pH
  - Report B states that "at some times of the year, acidification has already reached a critical threshold for organisms living on Alaska's continental shelves" and certain calcifiers are at risk of failure to build shells. Furthermore, loss of oyster spat further south (in Washington) is detrimental to oyster farmers in Alaska who use those spat (pg. 522).
  - Report B notes that oceans have become 30% more acidic globally (pg. 522) and uses the same statistic as Report K, that a 10% decrease in pteropod population can reduce adult weight of pink salmon by 20% (pg. 522).
  - Report C broadly discusses the negative impacts of ocean acidification on organisms that depend on calcification, which can be limited by a decrease in calcium carbonate in more acidic waters (pg. 11).

- Globally ocean pH has decreased from 8.17 to 8.09 over the past 200 years and could drop another 0.5 in this century if CO_2 rates continue to rise (pg. 11).
- They predict at those levels the oceans would see a 60% decrease in available calcium carbonate which could lead to a large decline in pteropods and other important food sources for salmon, whales, and other important species along the shores of south-central and southeast Alaska (pg. 11).

- Report K indicates that observations as far north as Kodiak (56ºN) have shown that the surface mixed layer (to 100m deep), is showing an average pH decline of 0.0017 units per year.
- Report K, using data from (Feely et al. 2009), projects that an atmospheric CO_2 concentration of 556 ppm would yield an ocean pH of 7.885, and an atmospheric CO_2 concentration of 834 ppm would lead to an ocean pH of 7.719 in the North Pacific (>50°N), with slightly less change in the Subpolar Pacific. These figures respectively represent a doubling and tripling of pre-industrial atmospheric CO_2 and ocean pH of 8.1 in the North Pacific and 8.0 in the subpolar Pacific (pg. 39).

- Ocean temperatures and circulation
  - Report C indicates that in the Chugach and Tongass National Forests, the most significant of potential impacts from increased ocean temperature are the possible changes to ocean currents and upwellings (pg. 10).
    - Melting glaciers may cause an increase in freshwater input which could shift the thermohaline circulation: "where water densities influenced by the combination of temperatures and salinity determine where water sinks, displacing deeper, warmer waters and causing up-wellings of nutrient-rich waters that drive the productivity of oceans in many locations" (pg. 10).
    - These changes could have major impacts on the ecology and productivity of important fisheries in south-central and southeast Alaska (pg. 10).
    - "These types of potential changes have such complexity and include variables that are [so] poorly understood that they cannot be presently predicted with any accuracy" (pg. 10).
  - Report C states that changes in ocean temperature will likely shift habitat quality for species, providing an increase in habitat for some and a decrease for others (pg. 11).
    - These changes will cause a shift in species distribution and subsequent human uses and access to those aquatic resources (pg.11).
  - Report K does not cite ocean temperature trends or future projections for Alaska's coastal and ocean waters, but notes that the global average increase in sea surface temperatures (SST) has been 1.1°F since 1950, and in British Columbia SST increases of 0.52 to 1.7˚F (0.29-0.94 °C), have been observed over the period 1915 to 2003 (page 44). Report K mentions that a warm-phase Pacific Decadal

Oscillation (PDO) is associated with increased ocean productivity in Alaska coastal waters, with the cool phase having the opposite effect (pg. 46).

- Report K notes that the most important currents in the region are the Alaska Current and the Alaska Coastal Current, and that "Sixty percent of the oxygen in the subsurface waters of the Alaskan Gyre was supplied by subarctic waters; the remaining 40% was supplied by subtropical waters" (pg. 52, 55) via the North Pacific Current (pg. 53). However, specifics on the dynamics of these systems are needed:
  - Models of future ocean currents and circulation as an information gap for the entire region (pg. 56)
  - Specific information about trends of storm frequency or intensity in Alaskan waters is lacking, the area could face "northward shifts in the Pacific storm track" with increased impacts to coastal areas (pg. 60).
  - Wind patterns, which drive nutrient upwellings along the continental shelf of the Gulf of Alaska, could face changes (pg. 82). Climate change impact on upwelling is cited as an information gap (pg. 84).
  - No information was available on observed or projected instances of hypoxic or anoxic conditions in Alaska oceans (pg. 92, 96).

- Marine Ecosystem Effects
  - Report K provides the following synthesis of effects in the Alaska Large Marine Ecosystem: "Recent changes in Alaska's coastal waters include general warming of ocean surface waters, warming of the southeast Bering Sea bottom waters over the continental shelf, a more strongly stratified ocean, hypothesized decrease in ocean productivity, alteration of pelagic ocean habitat and changes in the distribution of species. These changes have the potential to affect the structure, function, productivity and composition of Alaska's marine ecosystems, which may negatively impact the protected marine species that live or migrate through these ecosystems (e.g. North Pacific right whale). In the Gulf of Alaska, Sigler, Napp, and Hollowed (2008) identify ocean acidification, as well as climate regimes and ecosystem productivity, as major climate-related concerns" (pg. 97).
    - Changes in glacial runoff could alter coastal circulation and biogeochemical fluxes, particularly dissolved organic carbon (pg. 99).
    - An important topic that is in need of ongoing research: the emerging understanding that glacially derived fine dust (known as "flour") is an important source of iron, a critical limiting nutrient for phytoplankton. Increased glacial melt may thus lead to increased primary productivity in the Gulf of Alaska (pg. 100). It is estimated that soluble iron load from the Copper River basin is 30 to 200 tons (pg. 102).
    - Vertical stratification of the ocean could occur as increased pulses of cold freshwater from glacial melt reach warmer seawater (pg. 100).

        - During a "warm" or "sardine" thermal regime in the 1970s-90s, zooplankton and salmon increased in Alaska waters (pg. 106).
        - Increases in productivity due to iron enrichment and/or increased upwelling activity could lead to a reduction in oxygen levels in the water, forcing some species to seek shallower habitats but potentially allowing for expansion of species that tolerate low-oxygen conditions (pg. 109-110).

- Tidewater marshes and near-shore habitats
    - Report B notes that warming oceans and reduced ice are leading to more ship traffic and therefore a heightened risk of ballast-water introduction of invasive species (pg. 522).
    - Report K observes that "Freshwater inflows into estuaries influence water residence time, nutrient delivery, vertical stratification, salinity and control of phytoplankton growth rates. Decreased freshwater inflows increase water residence time and decrease vertical stratification and vice versa" (pg. 49).
    - Report K concedes that much information is still needed on the precise nature of nearshore impacts such as erosion and sedimentation. However, this source generalizes that changes in sea level rise and coastal erosion could impact low-lying habitats via destruction or saltwater intrusion, reducing staging areas for shorebird and waterfowl migration. SLAMM modeling indicates that while the impacts of SLR will likely be small overall in coastal Alaska, tidal swamps and flats are disproportionately affected because they are so low-lying (pg. 126-7).

Wildlife

- Salmon/other fish
    - Report B mentions that some species of salmon have expanded their ranges northward, but does not specify which (pg. 522).
    - Report B notes that Chinook salmon may alter their migration times and patterns, complicating management of the species (pg. 522).
    - Report H describes the potential effects of climate change on the five species of Pacific salmon in southeast Alaska. The key findings are (Pg. 183):
        - Pink salmon:
            - Increased frequency and extent of pre-spawner mortality resulting from increasing temperatures and decreasing summer flows.
            - Earlier emergence time and entry into the marine environment with less favorable conditions for early feeding and growth.
            - Deterioration of spawning habitats.
                - Greater upslope landslide activity increasing scour and sediment infiltration.
                - Incursion of saltwater from rising sea levels into spawning areas.

        - Alterations in sediment dynamics with changes in sea level.
    - Alterations in run timing as a result of shifts in temperature and discharge.
    - Report K adds that a 10% increase in water temperature would lead to a 3% drop in body weight, but that acidification impacts to pteropods would have a 20% drop in body weight (pg.164).
- Sockeye salmon:
    - Shifts in spawning time with subsequent changes in time of emergence of fry.
    - Spawning habitat deterioration from upslope landslides induced by increased rainfall intensity.
    - Changes in growth and survival resulting from alteration of trophic status of lakes.
        - Shifts in zooplankton availability.
        - Changes in lake physical and chemical dynamics resulting from either increases or decreases in water recharge.
        - Decreasing rearing capacity and secondary production from saltwater intrusion.
    - Increased predation as thermal characteristics become more favorable for natural or introduced predators.
- Chinook salmon:
    - Changes in run timing forced by temperature and/or discharge regimes.
    - Increased stress and mortality during spawning migration resulting from loss of thermal refuges in large pools.
    - Deterioration of spawning habitat caused by increased frequency of upslope landslides.
    - Loss of rearing habitat as thermal refuges.
- Coho salmon:
    - Deterioration of spawning habitat from landslides that scour spawning beds and deposit sediment on downstream spawning areas.
    - Changes in fry emergence timing and emigration.
    - Effects of climate change induced temperatures on growth and survival of juvenile Coho salmon.
        - Increased growth as temperatures in streams increase above 10°C but remain below 18°C.
        - Decreased survival as metabolic demands increase but food supplies become limited.
    - Loss of rearing habitats:

        - Decrease in summer rearing habitats as flow decreases and pool abundance and quality decrease.
        - Deterioration of off-channel habitats as temperatures exceed optimum ranges.
        - Loss of off-channel habitats through more frequent high intensity rainfall events that remove in-stream structure and beaver dams during fall and winter.
        - Intrusion of salt water into low elevation rearing areas.
    - Report K adds that important freshwater habitat for juvenile coho in the lower Taku River of Alaska would be inundated or turned too saline by 3-foot SLR (pg. 164)
- Report J mentions that grayling and trout are particularly susceptible to the effects of climate change (pg. 123).
- Report J also contains an extensive section on salmon, but that information is derived from Bryant 2009, which is "Report H" in this synthesis, outlined in detail above. This information is not repeated in the synthesis; however Report J's summary table has been reproduced as Appendix 1.
- Despite Report J's focus on freshwater ecosystems, much of the discussion in the ecological effects chapter is centered around terrestrial species like the marmot, which is also discussed in Report G (see "Mammals" below).
- Report K states: "Pacific salmon production in Alaska is inversely related to that on the West Coast (i.e., Washington, Oregon, California) and is climate-driven. The loadings on the British Columbia Pacific salmon catches suggest that those stocks occupy a transitional region, with Chinook and coho salmon of the same sign as the southern stocks and the three other species (sockeye, pink, chum) of the same sign, but in a smaller magnitude as do the Alaska stocks. For example, in the Pacific Northwest, the cool phase of the Pacific Decadal Oscillation (PDO) during the years 1947-1976 coincided with high returns of Chinook and coho salmon to Oregon rivers. Conversely, during the warm PDO cycle that followed (1977-1998), salmon numbers declined steadily." (pg. 161)
- Report K projects that: "If the regional impacts of global warming are expressed in El Niño-like or PDO-like ways, warmer waters due to global warming are likely to promote increased production of salmon in Alaskan waters, at least initially, provided primary and secondary production does not decline, while promoting decreased salmon production for salmon populations in the Pacific Northwest region (and throughout the California Current System). A key uncertainty here is how global warming will influence the characteristics of atmospheric surface pressure and wind fields over the North Pacific because of the prominent role that wind forcing plays in structuring the upper ocean." (pg. 163)

- Report K says "Under a doubling of CO_2, models predict that Pacific salmon would experience a range decline as they move northward into the Bering Sea and the Arctic" (pg. 164)

- Birds
  - Report B finds that reductions in the area of lakes and may reduce breeding habitat for migratory ducks and geese (pg. 520).
  - Report G reports multiple observed and potential impacts on bird communities:
    - Beetle-kill of white spruce trees in the Copper River basin reduced the density of ruby-crowned kinglets (pg. 263)
    - Longer growing seasons benefit trumpeter swans, but may lead to range shifts that bring them into competition with tundra swans (pg. 288)
    - It is anticipated that some species of forest birds (e.g., blue grouse) may benefit from climate change, but that flycatchers and other flying-insect-eating birds may be at risk from drought (pg. 297)
    - Tundra-dependent birds like white-tailed ptarmigan may decline or disappear from some locations (pg. 298).
    - Kittlitz's murrelets are undergoing a population decline of about 18% per year: "Kittlitz's murrelet feeds in waters around tidewater glaciers and is considered a critically endangered species as glaciers recede." (pg. 155)
    - Harmful algal blooms, specifically Pseudo-nitzschia (which causes domoic acid poisoning), which are projected to worsen with warming have had documented negative impacts to marbled murrelets (however it was unclear from the text where in the Pacific LCC they are or might be affected). (pg. 155)
  - Report K states that black oystercatchers are threatened by SLR throughout their breeding range because they nest on beaches (pg. 155). Shorebirds are generally vulnerable due to their extensive use of habitats that are at risk from SLR (pg.157)
  - Report K indicates that low reproductive rates and the observed impacts of temporary ocean changes in timing or amount of food availability (due to PDO, ENSO, etc.) on reproductive success indicates that this class of birds is generally susceptible to climate change (pg. 156). Cassin's auklet and common murre (guillemot) were cited as examples (pg. 157)

- Marine species
  - Report K notes that jumbo squid have been sighted in Alaska waters after 2003 (pg. 135)
  - Report K notes wide variation in modeled effect of climate change on fisheries productivity in Alaska, from a 6% decrease to 100% increase. (pg. 138)

- Report K states that effects of acidification on marine life are projected to be felt early in the North Pacific, due to already low carbonate saturation through much of the water column; thus making the building of shells more difficult (pg. 142)
- Report K observes that continental shelf marine ecosystems in the North Pacific exhibit temperature-drive (ie, associated with PDO) shifts between "crustacean/small pelagic fish"{cold} and "groundfish" {warm} communities (pg. 144). In the future, the system might transition permanently to a warmer water assemblage (pg. 147).
- Report K says that the effect of climate change on shellfish, eelgrass and plankton, in Alaska is an area where more information is needed (pg. 171, 173, 175).

- Mammals
  - Report B mentions that increased fire frequency could improve habitat for species that rely on berries, mushrooms and early successional vegetation, but is bad for species like caribou that rely on slow-growing lichens. (pg. 521)
  - Report G lists multiple observed and projected impacts to mammals:
    - Muskrats may have an advantage over competitors, due to feeding on sedges rather than grasses. The former will benefit from warming due to photosynthetic biochemistry (C3 vs C4) (pg. 253).
    - Beetle-kill of white spruce trees in the Copper River Basin reduced the density of red squirrels (pg. 263).
    - Body size of masked shrews has increased since 1950, possibly due to improved food availability (pg. 272).
    - Winter habitat quality for moose may be declining in the western Copper River Delta, as tall willows that are important for forage in deep snow are replaced by Sitka spruce (pg. 275, 283).
    - The extent and nature of the impact of climate change to a number of mammal species (e.g., black-tailed deer, moose, mountain goat, Northwestern deermouse, long-tailed vole, common shrew, and black and brown bears) will be determined by changes to the depth and duration of snow cover (pg. 281).
    - Increased forest disturbance due to warming could further fragment habitat for the Wrangell Island red-backed vole, which avoids clearcuts and other open areas (pg. 281-2).
    - Continued warming and decreases in soil moisture will decrease fungal communities that provide a food source for small mammals (pg. 282).
    - Little brown bat populations will likely expand northward (pg. 282).
    - Models project steep decline (87% by 2099) and fragmentation of Alaska marmot habitat statewide (pg. 282).
    - Black-tailed deer could benefit from longer growing seasons. The interplay between ungulates, vegetation and wolves will be complex. (pg. 282)

        - Salmon response to warming and snowpack changes will have cascading effects for its predators, including brown bears, bald eagles, mink and American marten (pg. 283).

Infrastructure

- Risk Management
    - Report F concludes that the use of GIS modeling is a critical tool for climate change adaptation efforts in transportation (Pg. 233).

Appendix 1. Report J contains this table summarizing potential effects to salmon (pg. 142), which itself is a summary of the contents of Report H.

Table 14. Summary of potential effects of climate change on anadromous salmonids in freshwater habitats of southeast Alaska.
Source: Reproduced from Bryant. (2009, Table 1, p. 183) by authors of this report.

Pink salmon and chum salmon

- Increased frequency and extent of pre-spawner mortality resulting from increasing temperatures and decreasing summer flows
- Earlier emergence time and entry into the marine environment with less favorable conditions for early feeding and growth
- Deterioration of spawning habitats
    - Greater upslope landslide activity increasing scour and sediment infiltration
    - Incursion of saltwater from rising sea levels into spawning areas
    - Alterations in sediment dynamics with changes in sea level
- Alterations in run timing as a result of shifts in temperature and discharge

Sockeye salmon

- Shifts in spawning time with subsequent changes in time of emergence of fry
- Spawning habitat deterioration from upslope landslides induced by increased rainfall intensity
- Changes in growth and survival resulting from alteration of trophic status of lakes
    - Shifts in zooplankton availability
    - Changes in lake physical and chemical dynamics resulting from either increases or decreases in water recharge
    - Decreasing rearing capacity and secondary production from saltwater intrusion
- Increased predation as thermal characteristics become more favorable for natural or introduced predators

Chinook salmon

- Changes in run timing forced by temperature and/or discharge regimes
- Increased stress and mortality during spawning migration resulting from loss of thermal refuges in large pools
- Deterioration of spawning habitat caused by increased frequency of upslope landslides
- Loss of rearing habitat as thermal refuges are lost

Coho salmon

- Deterioration of spawning habitat from landslides that scour spawning beds and deposit sediment on downstream spawning areas
- Changes in fry emergence timing and emigration
- Effects of climate change induced temperatures on growth and survival of juvenile coho salmon
    - Increased growth as temperatures in streams increase above 50°F (10°C) but remain below 64°F (~18°C)
    - Decreased survival as metabolic demands increase but food supplies become limited
- Loss of rearing habitats
    - Decrease in summer rearing habitats as flow decreases and pool abundance and quality decrease
    - Deterioration of off-channel habitats as temperatures exceed optimum ranges
    - Loss of off-channel habitats through more frequent high intensity rainfall events that remove instream structure and beaver dams during fall and winter
    - Intrusion of salt water into low elevation rearing areas

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