

# CLIMATE CHANGE: PREDICTED IMPACTS ON JUNEAU

Report to:

Mayor Bruce Botelho and the City and Borough of Juneau Assembly

Scientific Panel on Climate Change  
City and Borough of Juneau

Brendan P. Kelly  
Thomas Ainsworth  
Douglas A. Boyce Jr.  
Eran Hood  
Peggy Murphy  
Jim Powell

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## EXECUTIVE SUMMARY

Globally, atmospheric temperatures are rising in large part due to increased greenhouse gases in the atmosphere. Temperatures in Juneau have increased as much as 3.6°F during the 20<sup>th</sup> century, with the largest increase occurring during the winter months. Rates of warming were higher in the later part of the 20<sup>th</sup> century, and Juneau's average winter time temperature rose by 1.5 - 3°F in the past 60 years. The average winter temperature in the City and Borough of Juneau reached the freezing point of water in the early 1980s. The average winter snowfall at sea level in the City and Borough of Juneau decreased from 109 inches to 93 inches in the past 60 years. The average winter precipitation including rain and snow (reported as inches of liquid water), however, increased by 2.6 inches or more.

Climate models, refined and validated using records of past climates, predict continued warming at rates that will depend on future emissions of greenhouse gases. The models predict that the City and Borough of Juneau will see overall warmer and wetter weather, particularly in Fall and Winter. The Juneau Icefield will continue to retreat. Global sea level is rising as a result of the melting of glaciers and ice sheets and the warming of ocean waters (thermal expansion). Over the next century, global sea level is projected to rise 0.3 ft to 3.0 ft. In the City and Borough of Juneau, however, the land surface is rising as a result of the loss of glacial ice (isostatic rebound), and the rate of uplift is greater than the projected rate of global sea level rise. Over the next century, the relative sea level in the CBJ likely will *decrease* between 1.0 and 3.6 ft.

Projections for Juneau include:

- Average air temperatures in Juneau will increase by approximately 10°F by the end of the current century.
- By the end of the 21<sup>st</sup> century, shrubs and trees will have colonized elevations currently characterized as alpine or tundra habitat in southeastern Alaska.
- Many ecological responses to climate change will not be predictable and some may be counterintuitive. For example, yellow cedar trees are freezing in spring as temperature warms due to a loss of insulating snow cover.
- Increasing temperature and precipitation likely will alter the ecology of salmon in southeastern Alaska. Early entry into the marine environment - when food resources are low or absent - will decrease growth and survival.
- Increased intensity and frequency of coastal storms will negatively impact shoreline and wetland nursery areas for many marine species.
- Changes in climate may out pace the capacity of some plants and animals to adapt, resulting in local or global extinctions.
- Rapid changes in the ecology of terrestrial and marine environments will alter commercial, subsistence, and recreational harvesting in ways that cannot be readily predicted.
- While large regions of Alaska are expected to suffer damage to infrastructure associated with rises in sea level, coastal erosion, melting of permafrost, and reductions in sea ice, those impacts will be minimal for the CBJ.
- Reductions in winter snow cover at lower elevations will negatively impact winter recreational activities in the CBJ.
- Limiting the impacts of greenhouse gas emissions will require reductions in the consumption of fossil fuels. Those reductions will negatively impact transportation to and within the CBJ.
- An audit of energy consumption in the CBJ will be needed to fully assess the impacts of climate change on the borough.
- Economic costs of community responses to climate change are likely to increase over time, and proactive responses will minimize negative impacts.

## INTRODUCTION

Recognizing the mounting consensus that rapid climate change poses substantial concerns for society, Mayor Botelho asked the University of Alaska Southeast's Vice Provost for Research to convene a panel of scientists to advise the City and Borough of Juneau on the present and projected impacts of climate change on Juneau. The scientific panel was asked to:

*Decide on Agreed Impacts.* The scientific panel will gather relevant factual information, including present impacts and potential future projections of Global Warming's effects on Juneau.

*Present Findings to the Public and Assembly.* The scientific panel should provide a forum for the public about Global Warming's likely impacts on Juneau.

*Make Recommendations to the Assembly.* The scientific panel should advise the assembly on whether to participate in any of the regional or national initiatives. In addition, it is free to make recommendations on other municipal public policy options respecting Global Warming.

The panelists agreed that before considering policy options with respect to climate warming, the Mayor, Assembly, and community need a neutral summary of what is known scientifically about current and future impacts. The panel has reviewed scientific reports on climate change and presents current and potential impacts to Juneau. The panelists preferred to refer to global *climate change* rather than global *climate warming* to emphasize that the manifestations of overall climate warming will be realized as heterogeneous changes in many climate variables.

Knowledge of the impacts of climate change is accumulating rapidly and new data and interpretations are being reported in the scientific and popular literature at an accelerating rate. It will be prudent for the community to continue to monitor developments in this field.

The City and Borough of Juneau Scientific Panel on Climate Change was made up of the following individuals.

Thomas Ainsworth  
Meteorologist in Charge  
NOAA/NWS Forecast Office  
Juneau, AK 99801-9230  
(801) 790-6804 [tom.ainsworth@noaa.gov](mailto:tom.ainsworth@noaa.gov)

Dr. Douglas A. Boyce Jr.  
Alaska Issues Coordinator  
Juneau Forestry Sciences Laboratory  
Pacific Northwest Research Station, USDA Forest Service  
Juneau, AK 99801  
586-7807 [daboyce@fs.fed.us](mailto:daboyce@fs.fed.us)

Dr. Eran Hood  
Assistant Professor of Hydrology  
University of Alaska Southeast  
Juneau, AK 99801  
796-6244 [eran.hood@uas.alaska.edu](mailto:eran.hood@uas.alaska.edu)

Dr. Brendan P. Kelly, Chair<sup>1</sup>  
Vice Provost for Research  
Dean of Arts and Sciences  
University of Alaska Southeast  
Juneau, AK 99801  
796-6510 [brendan.kelly@uas.alaska.edu](mailto:brendan.kelly@uas.alaska.edu)

Peggy Murphy  
Juneau, AK  
586-5608 [pmndak@att.net](mailto:pmndak@att.net)

Jim Powell  
Wetlands and Stormwater  
Water Division, Alaska Department of Environmental Conservation  
Juneau Alaska 99801-1795  
465-5321 [jimpowell@gci.net](mailto:jimpowell@gci.net)

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<sup>1</sup> Temporary address (through 2008):  
Office of Polar Programs  
National Science Foundation  
4201 Wilson Blvd., Suite 755  
Arlington, VA 22230

Many of our colleagues generously contributed to our efforts including:

Mr. Dave Albert  
Dr. Colin Beier  
Dr. Mason Bryant  
Mr. Richard Carstensen  
Ms. Britteny Cioni  
City and Borough of Juneau Energy committee  
Mr. David D'Amore  
Mr. Bill Eichenlaub  
Dr. Paul Hennon  
Dr. John Karinen  
Mr. Edwin Knuth  
Dr. Chris Larsen  
Mr. Peter Larsen  
Mr. Bill Leighty  
Dr. Michael McClellan  
Dr. Roman Motyka  
Mr. Edward Neal  
Dr. Winston Smith  
Mr. Chad Soiseth  
Dr. S. James Taggart  
Mr. Brian Tassia  
Dr. Trista Patterson  
Dr. Sanjay Pyare  
Ms Gayle Wood

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## **GLOBAL CLIMATE DRIVERS**

The earth's climate is driven by solar energy reaching the earth and the amount of that energy that is reflected back to space. The amount of solar energy reaching earth varies on several time scales. Milutin Milankovitch described three major planetary cycles (now known as the Milankovitch Cycles) that influence the climate and glacial cycles on earth. The eccentricity – or degree to which the planet's orbit is elliptical – varies on a cycle of 100,000 years. The axial tilt (obliquity) - the degree to which the planet tilts toward the sun - varies over a 41,000 year cycle. Precession – the amount of wobble in the earth's rotation – has a periodicity of 23,000 years. The effect of all three cycles is evident in the record of global climate and ice age cycles (Figure 1).

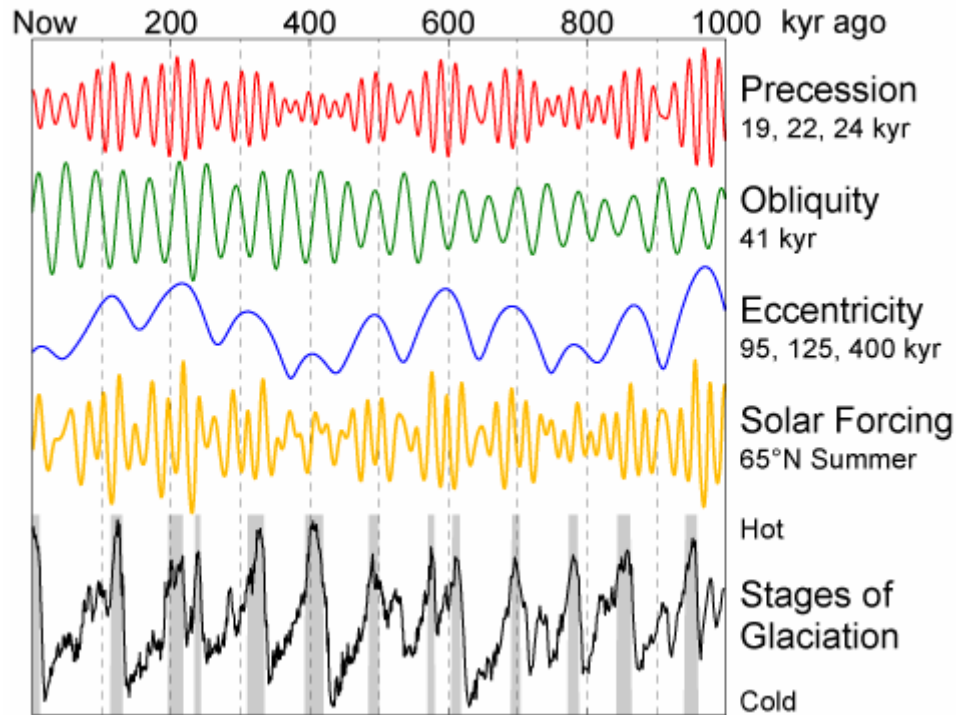


Figure 1. Precession, obliquity, and eccentricity describe variations in the earth's relationship to the sun on several time scales shown in thousands of years. The combined effects are cyclic changes in the amount of sun energy reaching the earth (solar forcing). Ice ages are primarily driven by that solar forcing.

The sun's energy reaches the earth primarily as short wave radiation, some of which can be absorbed by the land, oceans, and atmosphere. The amount of radiation that is absorbed versus reflected depends on properties of the earth's surfaces and of the atmosphere. The proportion of shortwave radiation reflected from a surface is its "albedo" and is as little as 10% for sea water and as high as 90% for snow. Thus, the snow covered surfaces of high mountains and latitudes reflect a great deal of energy while forests and oceans absorb most of the solar energy they receive. Ultimately, much of the shortwave radiation absorbed by the earth and atmosphere is returned to space as long wave radiation.

A variable portion of the heat radiated from the earth is trapped by certain gases (carbon dioxide, methane, water vapor, nitrous oxide, ozone) in the atmosphere that are translucent to the incoming short wave radiation but that absorb and counter-radiate the outgoing long wave energy. Those gases, thereby, have a similar heat-trapping effect as

glass surrounding a greenhouse, hence, the name “greenhouse gases.” The concentration of greenhouse gases in the atmosphere has varied between 150 and 300 parts per million (ppm) throughout at least the last 1,000,000 of the earth’s history. In the past 200 years, however, the burning of fossil fuels has increased atmospheric greenhouse gas concentrations higher than any levels in the past 650,000 years or more (IPCC 2001; Siegenthaler *et al.* 2005). Atmospheric carbon dioxide, for example, is 27% above pre-industrial levels (Siegenthaler *et al.* 2005). There is some evidence that agricultural activities, including forest burning and flooding to create rice paddies, increased greenhouse gases and contributed to climate warming as early as 8,000 years ago (Ruddiman 2003), although others have argued that those earlier warmings had other causes (Brook 2005).

The earth’s atmosphere, water, and land heat and cool at different rates as we spin toward, and then away from, the sun. This ‘differential heating’ leads to an uneven distribution of atmospheric temperature and pressure around the globe. Winds are created when temperature and pressure gradients move air from “high pressure” areas toward “low pressure” areas. The winds move air masses of varying temperature and moisture content horizontally and vertically, leading to an uneven distribution of clouds and precipitation.

The American Meteorological Society defines climate as the slowly varying aspects of the hydrosphere (bodies of water), and lithosphere (land surfaces), and atmosphere (gases). The term climate is commonly associated with the statistical description of weather variables, such as temperature and precipitation, over long periods of time (years, decades, and centuries). Climate also encompasses long term variability of our oceans (e.g., sea surface temperatures, sea level elevation) and land masses (e.g., deforestation and urbanization).

Causes of *climate variability* are generally grouped into three types: natural external forcings, natural internal forcings, and human-caused forcings.

- 1) Natural external forcings on the climate system include changes in solar emissions and slow changes in the earth's orbital elements (Milankovitch Cycles);
- 2) Natural internal forcings on the climate system include drought, volcanic ash, smoke from forest fires, and ocean-atmosphere oscillations (e.g., El Niño-Southern Oscillation);
- 3) Human-caused forcings to the climate system include increased greenhouse gas emissions, deforestation, and urbanization.

Important *natural internal forcing* that affect climate variability in the CBJ are the coupled ocean-atmosphere oscillations. El Niño-Southern Oscillation (ENSO) is a familiar example of these large-scale phenomena.

El Niño and La Niña represent opposite extremes in the naturally occurring climate cycle referred to as the ENSO. ENSO is an example of climate variability that has a time scale of 2-7 years. El Niño and La Niña are associated with opposite extremes in rainfall and sea-surface temperatures across the central and east-central equatorial Pacific (Figure 2). Sea surface temperature is important because warmer bodies of water are favored regions for deep atmospheric convection and storm generation.

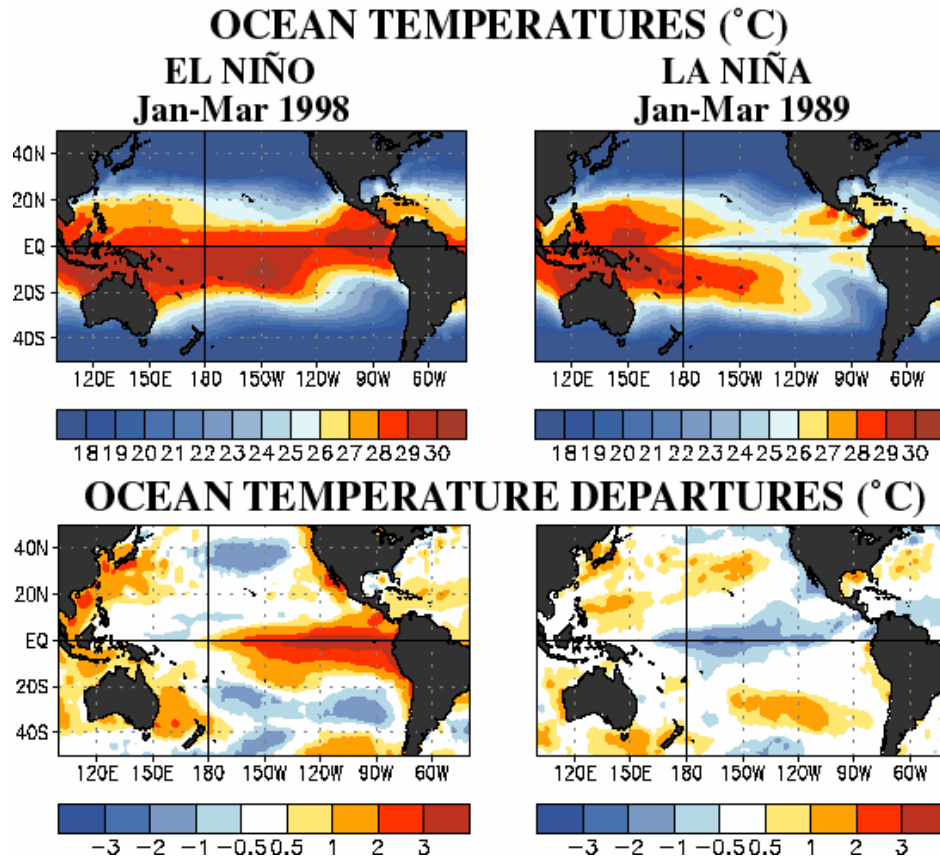


Figure 2. El Niño conditions coincide with an expansive pool of warm surface water stretching across the tropical and subtropical Pacific Ocean (top left) with sea surface temperatures more than 0.9°F above average in the central and eastern equatorial Pacific (bottom left). During La Niñas, a smaller pool of warm surface water forms (top right), and sea surface temperatures in the central and eastern equatorial Pacific are colder, by at least 0.9°F, than average (bottom right).

ENSO refers to even larger-scale fluctuations in air pressure anomaly over the equatorial Pacific between Tahiti and Darwin, Australia. Lower-than-normal air pressure at Tahiti and higher-than-normal air pressure at Darwin coincide with a typical characteristic of El Niño: abnormally warm water temperatures over the central and eastern Pacific (Figure 3). Conversely, higher-than-normal air pressure in Tahiti and lower-than-normal air pressure in Darwin coincide with abnormally cold ocean waters across the eastern tropical Pacific, typical of La Niña episodes.

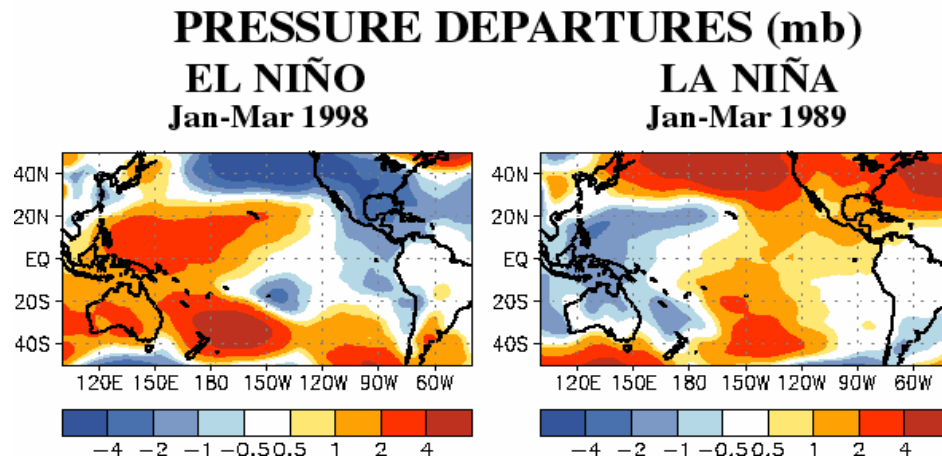


Figure 3. El Niño conditions (left) arise when higher-than-average air pressures (orange) persist over the tropical western Pacific Ocean and lower-than-average pressures (blue) prevail over the central and eastern tropical Pacific. Pressures over the North Pacific and Gulf of Alaska also are lower-than-average during El Niños. La Niña conditions (right) arise when lower than average air pressures persist over the tropical western Pacific Ocean and higher than average pressures occur over the central and eastern tropical Pacific. Pressures over the North Pacific and Gulf of Alaska also are higher-than-average during La Niñas.

During El Niño, the Pacific warm pool stretches farther east, and there is also lower-than-average pressure in the North Pacific and Gulf of Alaska known as the ‘Aleutian Low’. The counter-clockwise wind flow around the Aleutian Low steers warm, wet air toward southeastern Alaska bringing warmer and wetter than average winters to the CBJ.

The high pressures in the Gulf of Alaska during La Niña result in clockwise wind flows, which steer wind from the north and northeast across the Alaska panhandle. Hence, La Niña patterns often correlate with CBJ winters that are less stormy and colder and drier than average.

Systematic, long-term changes in climate may be caused by both natural and unnatural forces. The overall climate has warmed rapidly during the 20<sup>th</sup> and 21<sup>st</sup> centuries, and an increasing awareness of climate change, and predictions that climate change will accelerate, have spawned considerable scientific research. Data on past climates have been important in understanding recent changes, and we now have a good record of the earth’s climate extending to 650,000 years ago. That long record is used to validate

mathematical Global Climate Models (GCMs), which then are used to predict future climates.

### **Juneau Setting and Climate**

The City and Borough of Juneau (CBJ) is located in the north-central portion of the Alaska panhandle, approximately 600 air miles southeast of Anchorage and 900 miles north of Seattle. As of the 2002 census, the CBJ had 30,903 residents (CBJ 2006). Juneau is accessible only by air and sea with no road connections to other southeastern Alaska communities or the Canadian interior. The CBJ encompasses approximately 3,250 square miles of which approximately 80% is land and 20% is water. The CBJ is bounded on the west by the Lynn Canal; on the east by the Canadian border; on the south by Point Cone; and on the north by the Haines Borough (Figure 4). The CBJ ranges in elevation from sea level to greater than 8,200 ft in the Coast Range along the Canadian boarder. The mountains to the east of Juneau are mantled by the Juneau Icefield encompassing 1,450 square miles of which 928 square miles are located within the CBJ boundaries. The Juneau Icefield is the fifth largest in North America (Sprenke *et al.* 1999) and is drained by 38 major glaciers including the Mendenhall Glacier in the Mendenhall Valley.

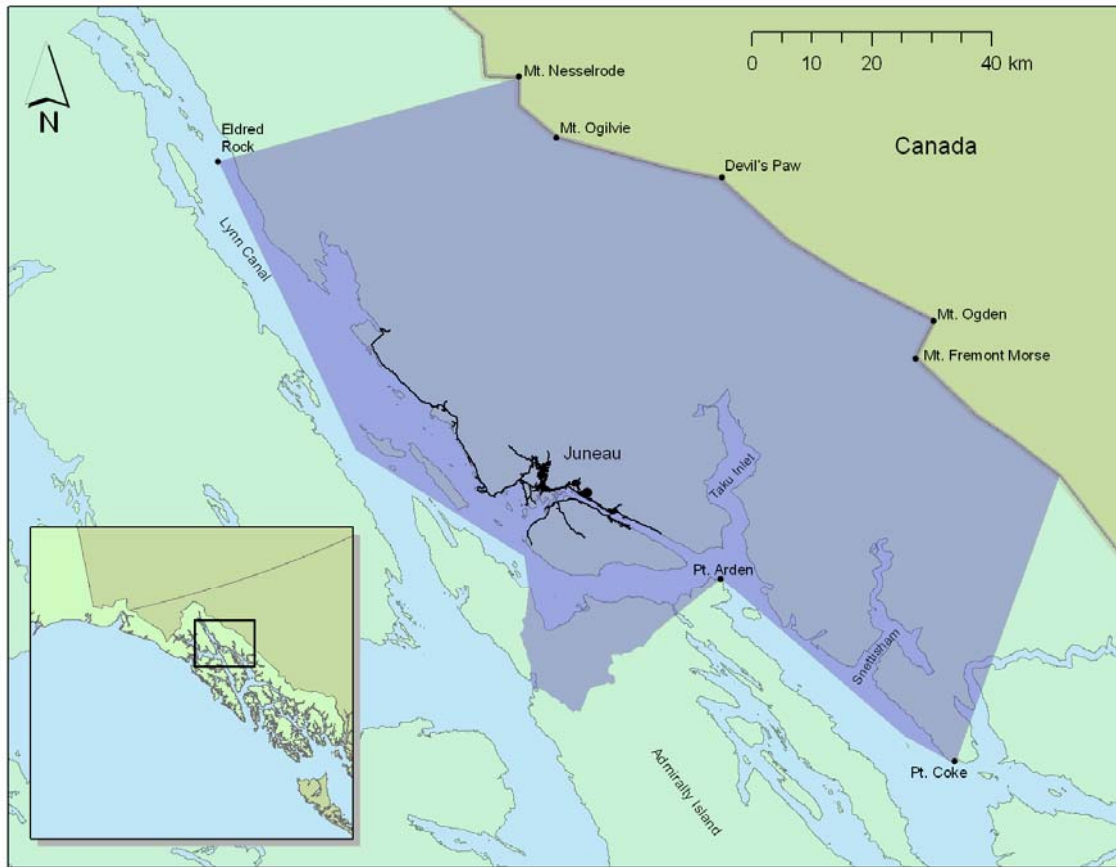


Figure 4. Extent of the City and Borough of Juneau in southeastern Alaska.

At the summer solstice, daylight in Juneau lasts for 18 hours and 18 minutes, while the sun is up on the winter solstice for only 6 hours and 21 minutes.

The climate of southeastern Alaska is classified as coastal rainforest. Annual temperatures vary little across the Alaska panhandle, but annual amounts of precipitation vary substantially. CBJ is in the path of most storms that cross the Gulf of Alaska. Because these weather systems remain in contact with the ocean for long periods of time, they are able to absorb - through evaporation - large amounts of water. Upon meeting the coastal mountain range, the moisture laden air is forced upward. As the air rises, it cools and the moisture condenses into clouds and eventually precipitation. Consequently, the area has little sunshine, generally moderate temperatures, and abundant precipitation. The rugged terrain exerts a fundamental influence upon local temperatures and the

distribution of precipitation, creating considerable variations in both within short distances.

The mean annual temperature in Juneau is 42°F based on 63 years of record. January is the coldest month with an average temperature of 26°F, and July is the warmest month with an average temperature of 57°F (Figure 5). Mean annual precipitation at the Juneau airport is 58 inches and peaks in October which averages greater than 8 inches of precipitation (Figure 5). Snowfall averages 93 inches per year at the airport and falls mainly between November and March with a peak in January (Figure 6). At sea level, snow cover is intermittent, while elevations above 1,000 ft often experience a continuous snow cover during winter and early spring. Snowfall on the Juneau Icefield can exceed 100 ft per year (Miller *et al.* 2003).

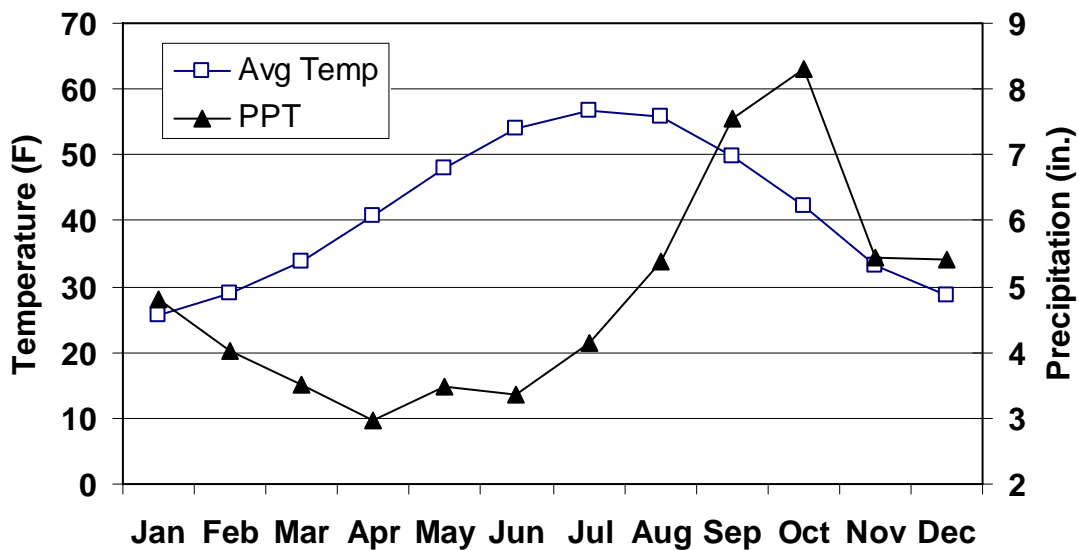


Figure 5. Monthly mean precipitation (PPT) and temperature at the Juneau Airport for the period 1943-2006. Data from NOAA climate database:  
<http://pajk.arh.noaa.gov/climatology/webcli.htm>

Weather affecting CBJ generally comes from over the ocean or from the interior. Air masses arriving from the Gulf of Alaska are moist and relatively mild. Air masses from the interior, on the other hand, are much drier and can have extreme temperature

variations. The coldest winter nights and warmest summer days typically coincide with weather patterns that drive air offshore from the interior. Extreme hot and cold spells in CBJ are generally brief lasting only a few days.

Wind flow across southeastern Alaska is influenced by the rugged terrain, and wind direction and speed are highly variable over very short distances. The strongest winds are almost always experienced over the water. Potentially damaging high winds are associated with two principal weather patterns that affect southeastern Alaska in the winter. During periods of extremely cold winter temperatures, gusty winds can blow from the northeast in excess of 60 mph. These winds, known locally as Taku Winds, are typically strongest between downtown Juneau and the Taku River, including Douglas. Similarly, gusty winds may be felt near other large east-west channels (e.g., Berners Bay, Icy Strait) but are rarely observed in the populated Mendenhall River valley. High winds also are favored when strong winter storms move north along the outer coast of the Alexander Archipelago. Such storms often originate from the tropical latitudes far to our south and west and are usually accompanied by warmer than average temperatures and heavy rainfall. When such strong winds have occurred at high tide (e.g., late November 1984), significant coastal flooding ensued.

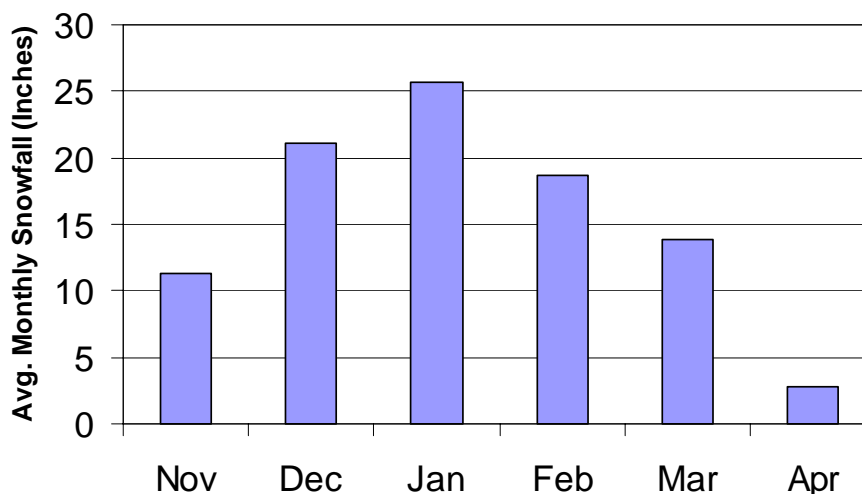


Figure 6. Monthly mean snowfall at the Juneau Airport for the period 1943-2006. Data from NOAA climate database: <http://pajk.arh.noaa.gov/climatology/webcli.htm>

The watersheds in developed portions of the CBJ include both glacial streams such as the Mendenhall River and Lemon Creek and non-glacial streams such as Montana Creek, Jordan Creek, and Gold Creek. In the glacial streams, streamflow closely tracks air temperature. As a result, most streamflow occurs in summer months when glacier melt and snowmelt are at a maximum, and the lowest flows in winter typically are 200-300 times lower than the highest flows of summer (Figure 7). Stream flow in non-glacial, clearwater streams such as Montana Creek is fed primarily by precipitation and groundwater, thus these streams demonstrate high flows during spring snowmelt and during the rainy months in the fall (Figure 7).

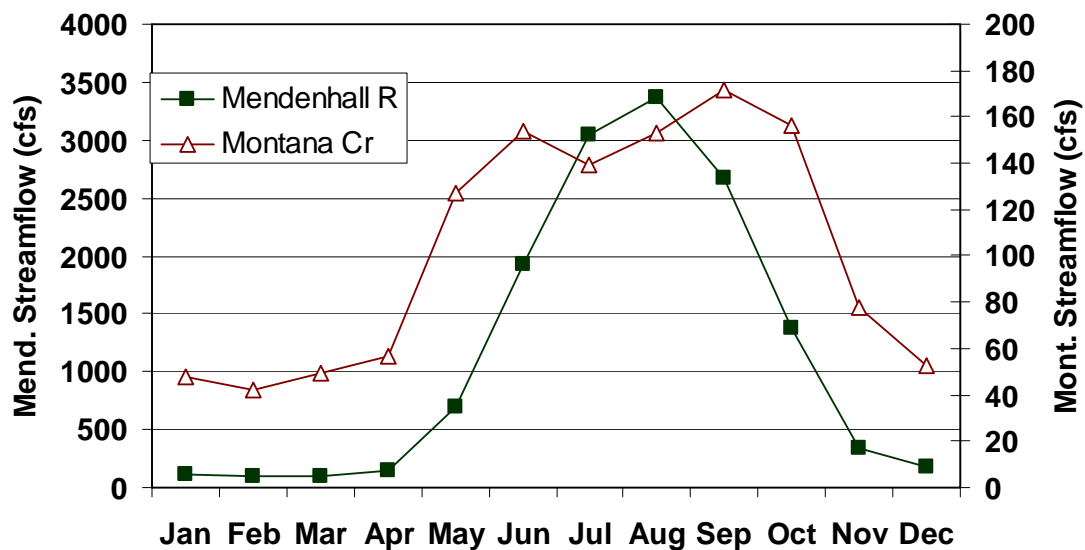


Figure 7. Monthly mean stream flow in cubic feet per second (cfs) for the glacial Mendenhall River and the non-glacial Montana Creek near Juneau, Alaska for 1965-2005. Data from USGS streamflow database for Alaska (<http://waterdata.usgs.gov/ak/nwis/sw>).

Land cover types within the CBJ include: estuary, beaches, beach meadows, wetlands, alpine tundra and blockfields, glacial ice and permanent snowfields, successional communities in glacial forelands, and upland coniferous forest. Vegetation in the upland regions of the CBJ is dominated by the coastal temperate rainforest typical of southeastern Alaska, consisting of Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*), with alder (*Alnus rubra*) growing in disturbed areas and riparian

corridors. Common under story flora include: devil's club (*Oplopanax horridum*), blueberry (*Vaccinium alaskense*), and salmonberry (*Rubus spectabilis*).

Southeastern Alaska is comprised of over 1,000 islands and a mainland partially isolated from the rest of the continent by ice fields. As a result, the terrestrial fauna is comprised of many endemic species (Klein 1965; Smith 2005), and the distribution of terrestrial vertebrates reflects the insular nature of the landscape. Only 8 species of amphibians are found in southeastern Alaska, and their distribution and status is poorly known (MacDonald 2003; Carstensen *et al.* 2003) but very likely reflects glacial history. Over 50 species of terrestrial mammals and 24 species of marine mammals occur in southeastern Alaska (MacDonald and Cook 1996).

The CBJ is a maritime community, and the surrounding fresh and marine waters support diverse ecosystems that directly influence local lifestyles. Juneau's climate and environment, as parts of a larger oceanic ecosystem, are influenced by natural physical forces such as currents, upwelling, down welling, precipitation, glacial melt, and runoff (Mundy 2005). Abundant, high quality fish habitats support all five species of Pacific salmon, and several species of trout are produced naturally in CBJ waters. Along the Juneau road system, eighty nine streams have been catalogued as anadromous streams by the Alaska Department of Fish and Game (Bethers *et al.* 1995). Harvest of salmon and other fish are important to Juneau's subsistence, commercial, and recreational fishers. Commercial fishing is a small sector of Juneau's economy, but it is expanding with sport fishing and charters generated by the cruise ship industry (JEDC 2005). During the past 20 years, the CBJ has received increasing revenues from fish taxes from local seafood processing (JEDC 2005). In FY 04, the CBJ tax receipts were \$234,336.

Prior to the 19<sup>th</sup> century, the Gastineau Channel was one of the main fishing grounds of the area's indigenous Tlingit population. Fishing was important to the Tlingit economy, which included a complex set of trading networks (Sepez, et. al. 2005). After the mid-19<sup>th</sup> century, American business and governmental interests expanded into the Alaska territory developing new commercial industries, including Alaska's commercial fishing

industry. Over time, recreational sport fishing also became economically important in the region.

In 2004, commercial vessels landed 5.4 billion pounds of fish statewide, 12.8 million pounds of which were landed in Juneau (US DOC 2007; Cathy Tide, CFEC, personal communication). Statewide, subsistence fishing accounts for approximately 40 million pounds and recreational fishing for around 7 million pounds (Vaccaro 2005). While their catch numbers are smaller, recreational and subsistence fisheries are fundamental to the economy and social dynamics of many Alaskan communities (Vaccaro 2005). The importance of subsistence, recreational, and commercial fisheries (including aquaculture and mariculture) to local values and economies in southeastern Alaska are described further in the Appendix.

## **CLIMATIC CHANGES**

### **The Global Climate Record**

Climate records older than a few hundred years depend mainly on inferences from environmental indicators of past climate. Instruments for measuring temperature, pressure, and humidity were first developed in Europe during the 17<sup>th</sup> and 18<sup>th</sup> centuries, and climate records from surface and satellite sensors span little more than 150 years. In the U. S., the first federal meteorological service program was assigned to the Army in 1870. Weather observations in Juneau started in June 1881, the year after gold was discovered in Gold Creek (USDA 1925).

Paleoclimatology is the study of climate prior to the widespread availability of measurement records of temperature, precipitation, and other parameters. Instead of instrument recorders, *environmental recorders* are used to infer past climatic conditions and thus extend our understanding far beyond the century and a half long instrumental record. “Proxy” records of climate can be retrieved from tree growth rings, the skeletons of tropical coral reefs, cores from glaciers and ice caps, and laminated sediments from lakes and the ocean. Those proxies have demonstrated cyclic variations in climate such as

major glacial advances in the northern hemisphere approximately every 100,000 years for the past 1 million years. Those glaciations were characterized by the advance of ice sheets – thousands of yards thick - southward from the Arctic and are thought to have been mediated by regular variations in the Earth’s orbit around the sun (Hewitt 2000; Shakleton 2000). Recent extraction of ice cores nearly 2 miles deep in Greenland and Antarctica indicated regular variations in atmospheric composition and temperature during the last 450,000 years (Figure 8; EPICA 2004).

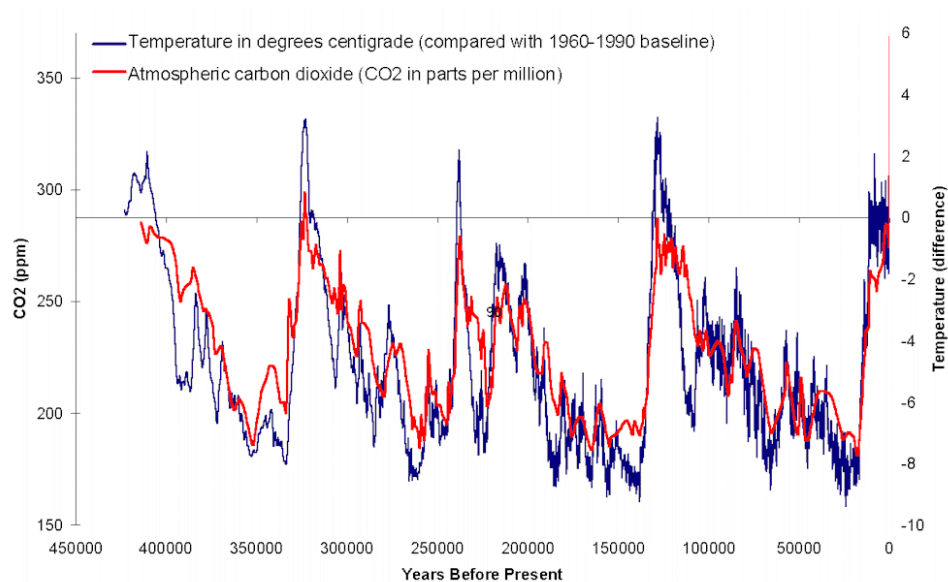


Figure 8. Reconstruction of atmospheric carbon dioxide levels and global temperature over the past 400,000 years using records from ice cores in Antarctica. Image from: <http://www.brighton73.freemove.co.uk/gw/paleo/>.

Carbon dioxide is a greenhouse gas that readily absorbs longwave (thermal) radiation that is re-radiated from the earth’s surface toward space, and long-term records show that fluctuations in CO<sub>2</sub> concentrations in the atmosphere are closely associated with changes in global temperatures (Figure 8). Concentrations of carbon dioxide (CO<sub>2</sub>) in the earth’s atmosphere, measured from Antarctic ice cores, have fluctuated between 150 and 300 ppm for the last 650,000 years (Siegenthaler et al. 2005). Since the beginning of the industrial revolution, however, CO<sub>2</sub> concentrations have increased rapidly from approximately 280 ppm to current levels of more than 380 ppm. This rapid increase in

atmospheric CO<sub>2</sub> concentrations over the last 150 years is unprecedented in the atmospheric record during the last 650,000 years both in terms of the rate of increase and the overall magnitude of CO<sub>2</sub> concentrations (Figure 9). The increase in CO<sub>2</sub> levels since the 1800s is associated with sharp increases in average atmospheric temperature in proxy data and in the instrumental record (Figure 10).

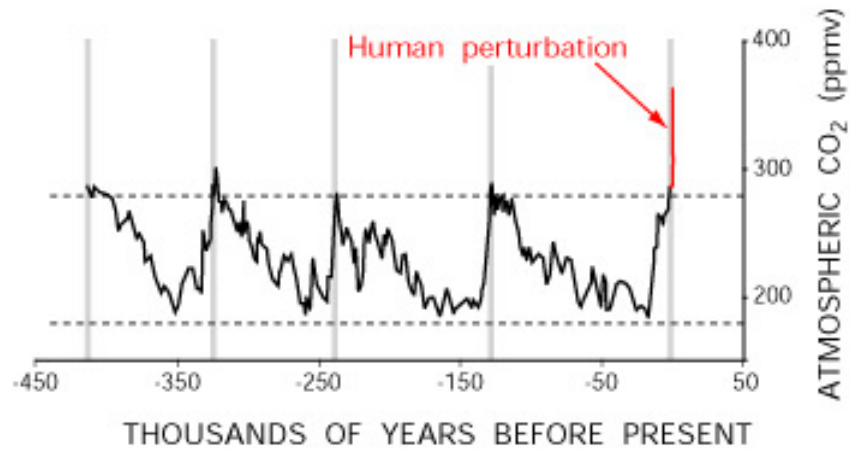


Figure 9. Atmospheric CO<sub>2</sub> concentrations from the past 400,000+ years as reconstructed from ice cores (black line) and recent measured concentrations (red line). Figure adapted from Falkowski *et al.* (2000) by the US Geological Survey (<http://pubs.usgs.gov/fs/fs026-03/fs026-03.html>).

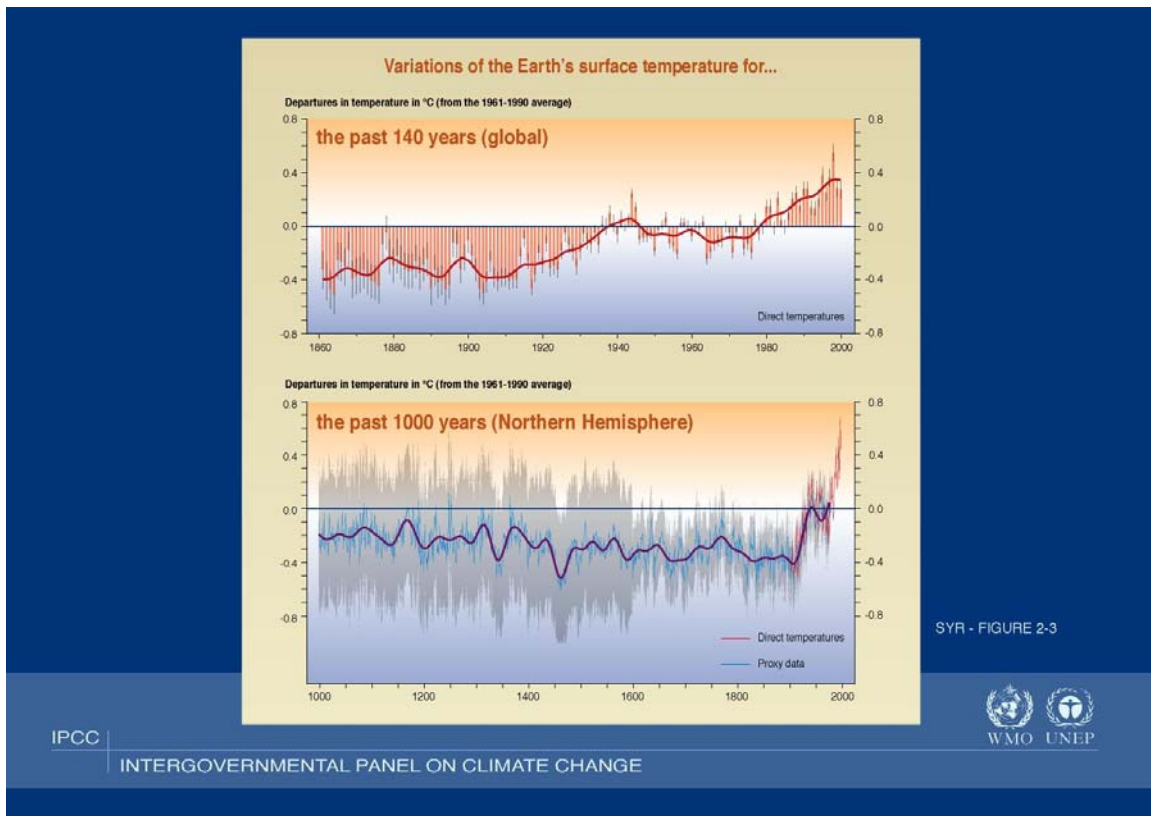


Figure 10. Departures from the 1961-1990 mean temperatures over past 140 years (top) and 1000 years (bottom) (IPCC 2001).

### Southeastern Alaska Climate Record

During the past fifty years, high-latitude regions such as Siberia, Alaska, and northern Canada have warmed more than any other regions on Earth, and the 20<sup>th</sup> century Arctic is the warmest of the past 400 years (Overpeck *et al.* 1997; Serreze *et al.* 2000). In addition, future increases in temperature are projected to be proportionally greater in the high latitudes (Roots 1989). The temperature increases observed at high latitudes are not fully understood, but are thought to involve cryospheric effects such as the snow/ice albedo feedback effect (e.g. Sturm *et al.* 2005), coupled with changes in the atmospheric circulation, and possibly ocean currents.

The last major glaciation that affected Alaska was the late Wisconsin glaciation, which peaked approximately 20,000 years ago. In that period, also known as the Last Glacial Maximum (LGM), glaciers occupied approximately 262,800 mi<sup>2</sup> in Alaska (total area:

656,245 mi<sup>2</sup>), nearly ten times the area occupied by glaciers today. Sea level during the LGM was approximately 400 ft lower compared to current sea level, and ice covered most of southeastern Alaska (Figure 11). Fossil remains of animals indicate that parts of southeastern Alaska's coast were ice free and inhabited by communities of terrestrial and marine mammals and birds throughout the LGM (Heaton and Grady 2003).

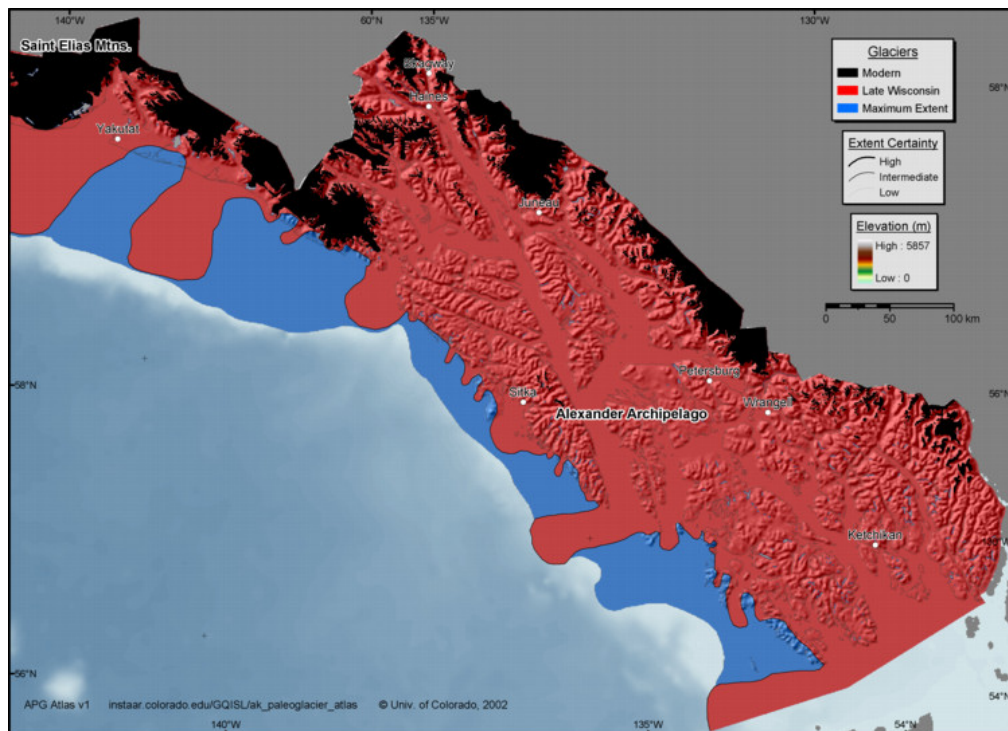


Figure 11. The extent of glaciers in southeastern Alaska during modern times (black), the late Wisconsin glaciation (~ 20,000 years ago; red), and the maximal extent reached during the last 3 million years by valley glaciers, ice caps, and the northwestern Cordilleran Ice Sheet (blue). From the Alaska PaleoGlacier Atlas project

[http://instaar.colorado.edu/QGISL/ak\\_paleoglacier\\_atlas/](http://instaar.colorado.edu/QGISL/ak_paleoglacier_atlas/)

More recently, glaciers in Alaska expanded during the Little Ice Age (LIA), a multi-century period of cooling that peaked in the late 18<sup>th</sup> century. Geomorphic markers such as trimlines and moraines indicate that during the LIA, glaciers throughout southeastern Alaska advanced, in some cases dramatically, beyond their present day locations. For example, at the peak of the LIA in the late 1700s, the terminus of the Mendenhall Glacier covered Mendenhall Lake and was located down valley from the current location of Back

Loop Road (Figure 12). At the same time, the Glacier Bay ice field extended beyond the mouth of Glacier Bay into Icy Strait (Figure 13).

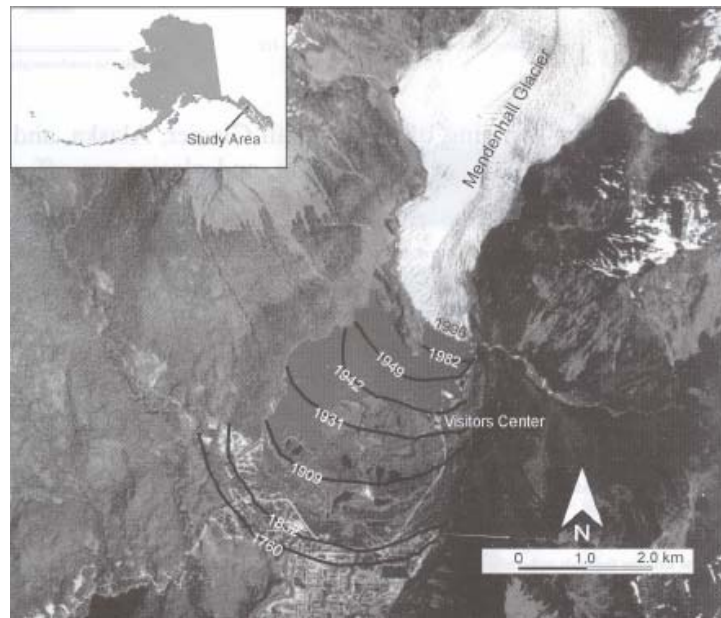


Figure 12. Location of the terminus of the Mendenhall Glacier since the peak of the Little Ice Age in the 1700s. Figure from Motkya *et al.* 2002.

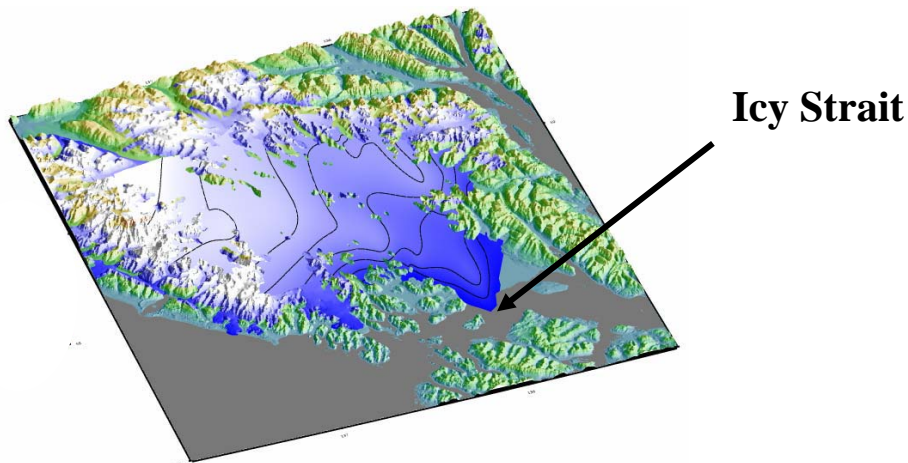


Figure 13. Glacier Bay ice field reconstruction. (Left) Field locations where data were gathered to reconstruct the extent of the Glacier Bay Ice Field. (Right) Reconstruction of the peak areal extent for the Glacier Bay Ice Field around 1750. Figure modified from Chris Larsen, University of Alaska Fairbanks Geophysical Institute, [http://www.giseis.alaska.edu/Input/chris/2panel\\_3d.jpg](http://www.giseis.alaska.edu/Input/chris/2panel_3d.jpg)

Since the end of the LIA, the Mendenhall Glacier has retreated approximately 2.8 miles up the Mendenhall Valley. In recent years, the rate of the Mendenhall's retreat appears to

have been increasing and has consistently exceeded 55-110 yards per year since the late 1990s. The retreat of glaciers in Glacier Bay since the end of the LIA has been far more dramatic. The collapse of the Glacier Bay Icefield has resulted in a loss of 727 cubic miles ( $3 \times 10^9$  tons) of ice since the late 18<sup>th</sup> century (Larsen et al 2005). That volume of melt water raised global sea level by 0.31 inches.

Instrumental temperature records in southeastern Alaska date back to the beginning of the 19<sup>th</sup> century at several sea level locations including Sitka and Juneau. Temperatures in Juneau have increased between 2.7 and 3.6°F during the 20th century, with the largest increase in temperature occurring during the winter months (Motyka *et al.* 2002; Larsen *et al.* 2007). Additionally, the rate of temperature change in southeastern Alaska increased in the later portion of the 20<sup>th</sup> century (Figure 14). The best fit regression suggests an increase of about 3°F during between 1940 and 2005. Long-term (30 year) averages suggest an increase of 1.5°F over that time. During the same time period, annual precipitation in Juneau increased (Figure 15) by 2.6 inches (30-year average) to over 10 inches (best fit regression). Taken together, these trends indicate that CBJ is shifting toward a warmer, wetter climate regime.

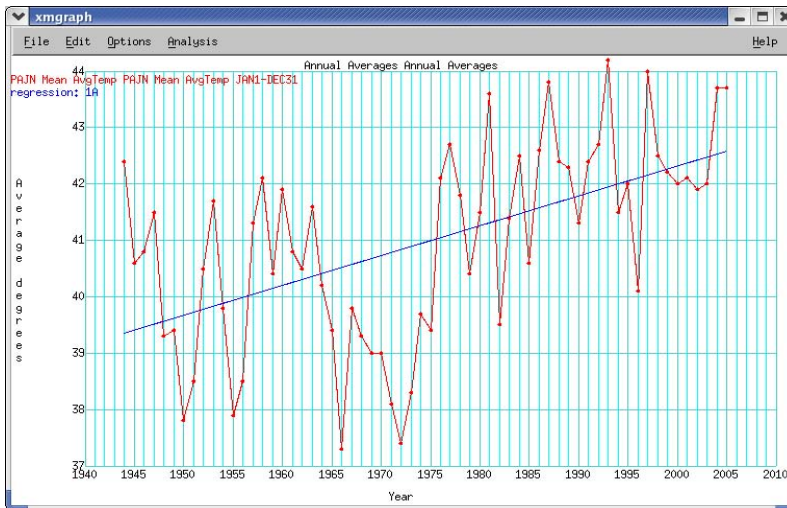


Figure 14. Annual average temperatures at Juneau International Airport 1943-2005 (red) and its regression line (blue) showing the best-fit relationship with temperature over time. The regression line indicates a warming trend overall (National Weather Service, Juneau).

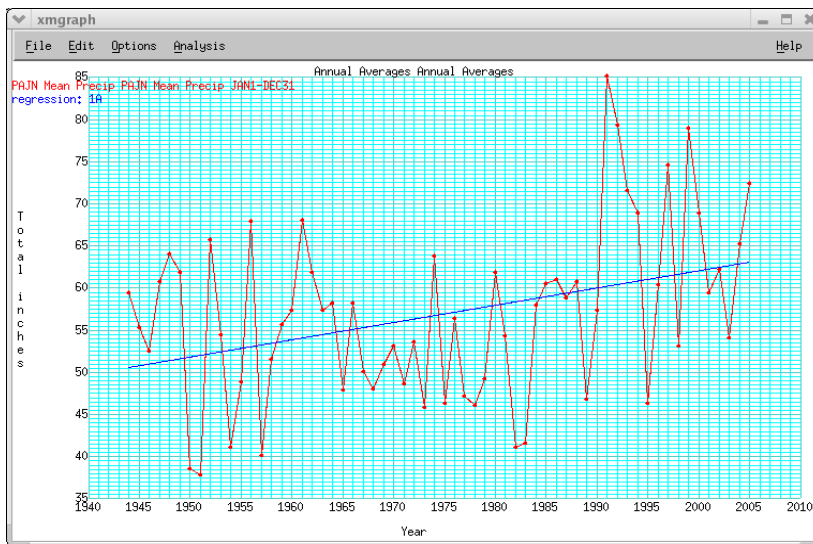


Figure 15. Annual precipitation at Juneau International Airport 1943-2005 (red) and its regression line (blue) showing the best-fit relationship with precipitation over time. The regression line indicates a wetter trend overall (National Weather Service, Juneau).

### Predicted climate changes for Juneau

Climatologists predict future climate based on sophisticated computer simulations. The effectiveness of the simulations is tested by comparisons with paleoclimatic records. Numerous climate models, developed by researchers in several countries, consistently predict a rapid and long term rise in global temperatures over the next century (IPCC 2001). Overall, the planet's radiation balance is increasing by 0.85 watts per square meter per year, causing the atmosphere to warm (Hansen *et al.* 2005). While the planet is warming overall, the effects will not be uniform due to complex interactions between atmospheric and oceanographic circulation. Some regions, such as the North Atlantic Ocean, likely will have lower average temperatures later this century (Bonsal and Prowse 2005). Thus, it is more informative to refer to *climate change* as opposed to *climate warming*.

The ongoing increase in atmospheric CO<sub>2</sub> concentrations is predicted to raise the overall average global temperature between 3.2 and 9°F in the coming century (Figure 16).

Current climate models predict a range of temperature increases, but all predict substantial warming.

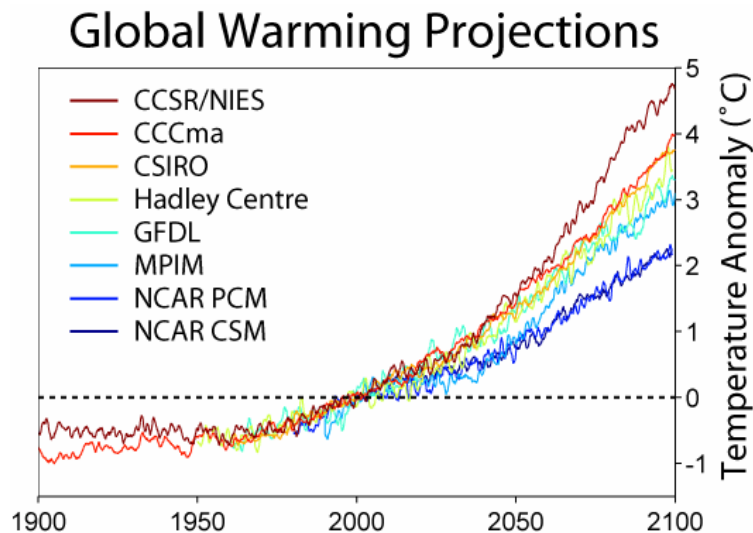


Figure 16. Predicted change in atmospheric temperature in the next century based on 8 different climate models. The *Special Report on Emissions Scenarios* was a report prepared by the Intergovernmental Panel on Climate Change (IPCC). Figure created by Robert A Rohde ([http://www.globalwarmingart.com/wiki/Main\\_Page](http://www.globalwarmingart.com/wiki/Main_Page)).

Precipitation is also expected to increase over the 21st century, particularly at mid-high latitudes of the northern hemisphere. As temperatures increase in the northeast Pacific and northwest North America, the atmosphere will be able to absorb more moisture from the ocean through evaporation. When that air is forced over the coast range, it will cool and condense the moisture out as precipitation, mainly in form of rain. Recent climate model results suggest that El Niño-like sea surface temperature patterns in the tropical Pacific are likely to be more persistent (National Climatic Data Center, NOAA, Global Warming: <http://lwf.ncdc.noaa.gov/oa/climate/globalwarming.html#Q4>). The El Niño - Southern Oscillation (ENSO) refers to the multi-year oscillation of sea surface temperatures and atmospheric pressure across the tropical Pacific. During the El Niño phase, sea surface temperatures are 0.9°F or more above average in the central and eastern equatorial Pacific for several months. Such conditions frequently result in increased storminess over the central and northeast Pacific.

Climate models project that, during the 21<sup>st</sup> Century, Alaska (and the Arctic as a whole) will warm at least twice as much as the rest of the world (Kattsov and Källén 2005). The warming is expected to be largest during the cold half of the year. According to the range of possible forcing scenarios, and taking into account uncertainty in climate model performance, the International Panel on Climate Change (IPCC) projects a global temperature increase of 2.5 – 10.4°F from 1990 – 2100. The warming will be heterogeneous with land areas warming faster than the oceans, particularly in high latitudes. Global climate models predict temperature increases close to 10°F for Juneau before the current century ends (Figure 17). The Pacific Northwest and southeastern Alaska are predicted to experience 50 to 70 fewer frost days per year (Figure 18).

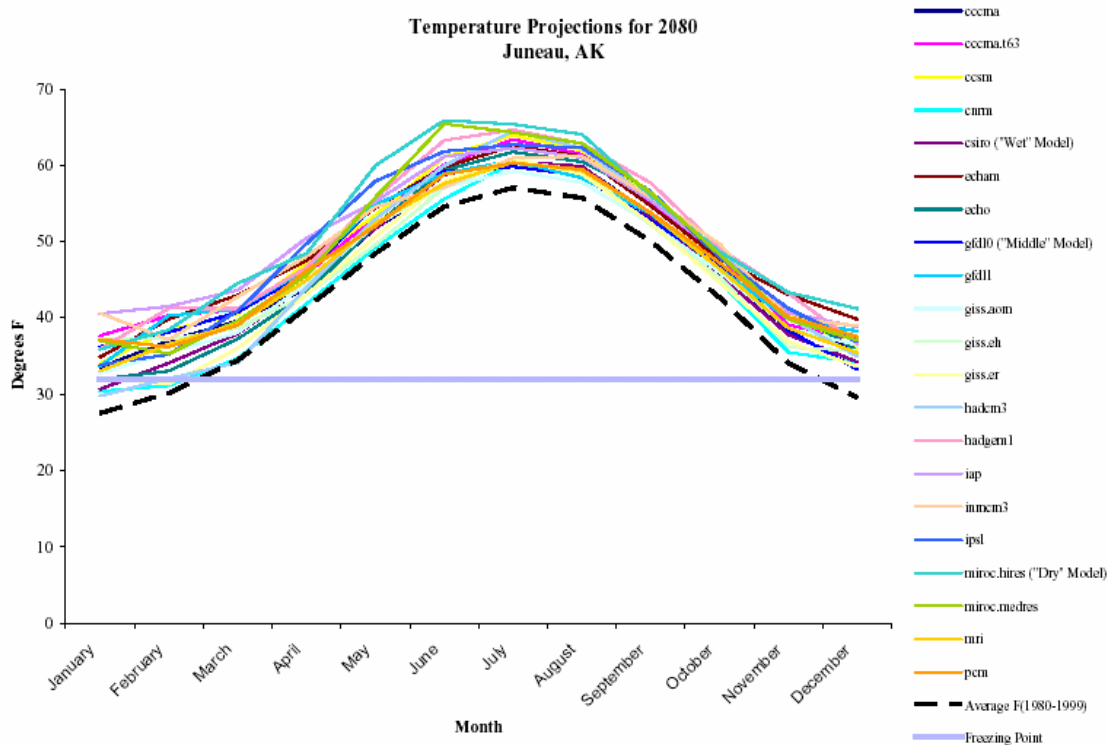
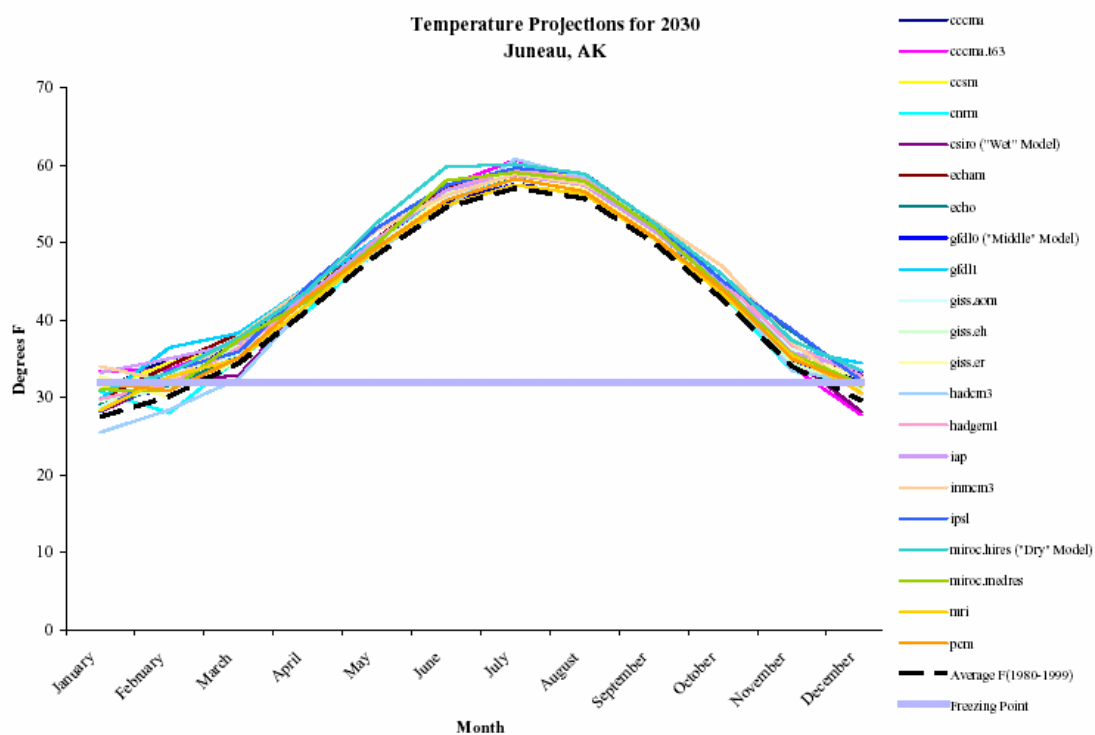


Figure 17. Average monthly air temperature for Juneau (dashed lines) and temperatures predicted for Juneau in the years 2030 (upper panel) and 2080 (lower panel) by 21

climate models (colored lines). Model outputs provided by Lawrence Livermore National Laboratory (PCMDI Collection), National Center for Atmospheric Research, and the Institute of Social and Economic Research at the University of Alaska Anchorage.

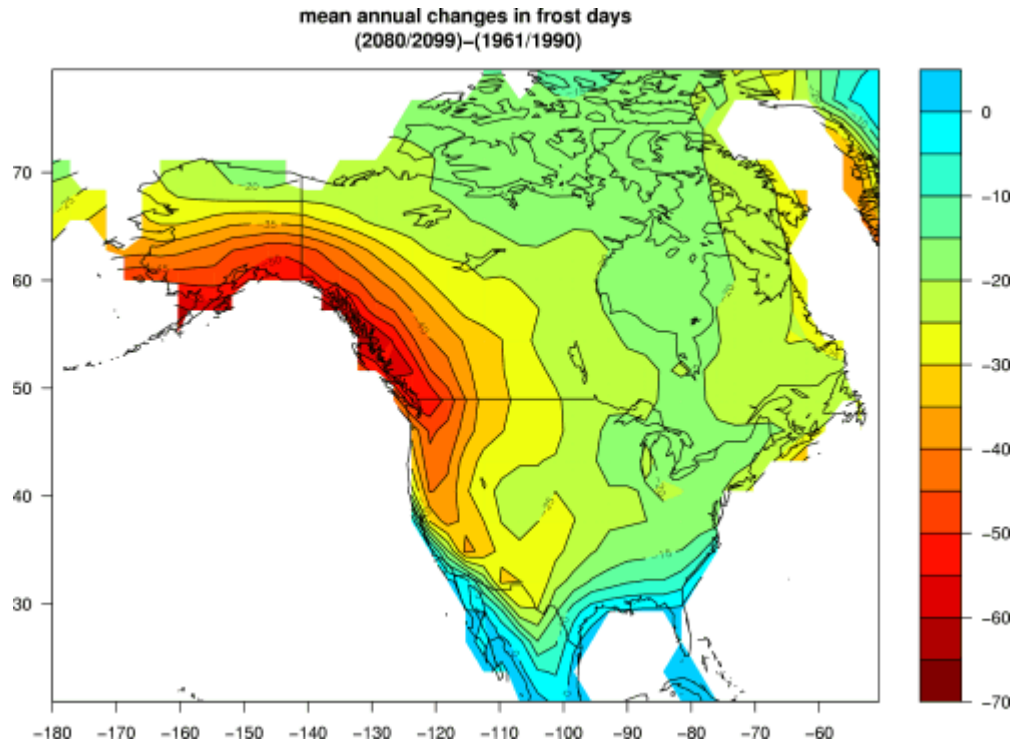


Figure 18. Mean changes in the annual number of frost days, computed as the difference between the 1961 - 1990 mean climate and means predicted for 2080 – 2099 by the National Center for Atmospheric Research’s Parallel Climate Model ([http://www.assessment.ucar.edu/modeling\\_scaling/index.html](http://www.assessment.ucar.edu/modeling_scaling/index.html)).

In southeastern Alaska, there is a strong interrelationship between precipitation and temperature. Climate models generally agree that precipitation, as well as air temperatures, will increase in southeastern Alaska this century (Figure 19). Although the array of predictions for precipitation is wider, models generally agree that liquid precipitation will increase and snowfall at lower elevations will generally decrease in southeastern Alaska over the next 50-100 years (Bonsal and Prowse 2006; Meehl et al. 2005). When temperatures are warmer than average in autumn and winter, Juneau experiences more precipitation (Juneau National Weather Service Forecast Office, unpublished data). Conversely, warmer springs and summers correlate with less than

average seasonal precipitation. The impact is somewhat greater in the fall and winter because 60% of Juneau's annual precipitation occurs between September and February. Hence, based on historical correlations, projections of warmer than average autumns and winters would be accompanied by wetter weather as well. On a broader scale, climate change is predicted to cause an intensification of the global hydrologic cycle because of increased evaporation associated with warmer temperature (Allen and Ingram 2002). A more intense hydrologic cycle, in turn, may lead to an increase in the frequency and magnitude of heavy precipitation events and floods (Easterling *et al.* 2000). The effects of hydrologic intensification on climate within CBJ are difficult to assess because of scale issues and thus are not discussed in this report.

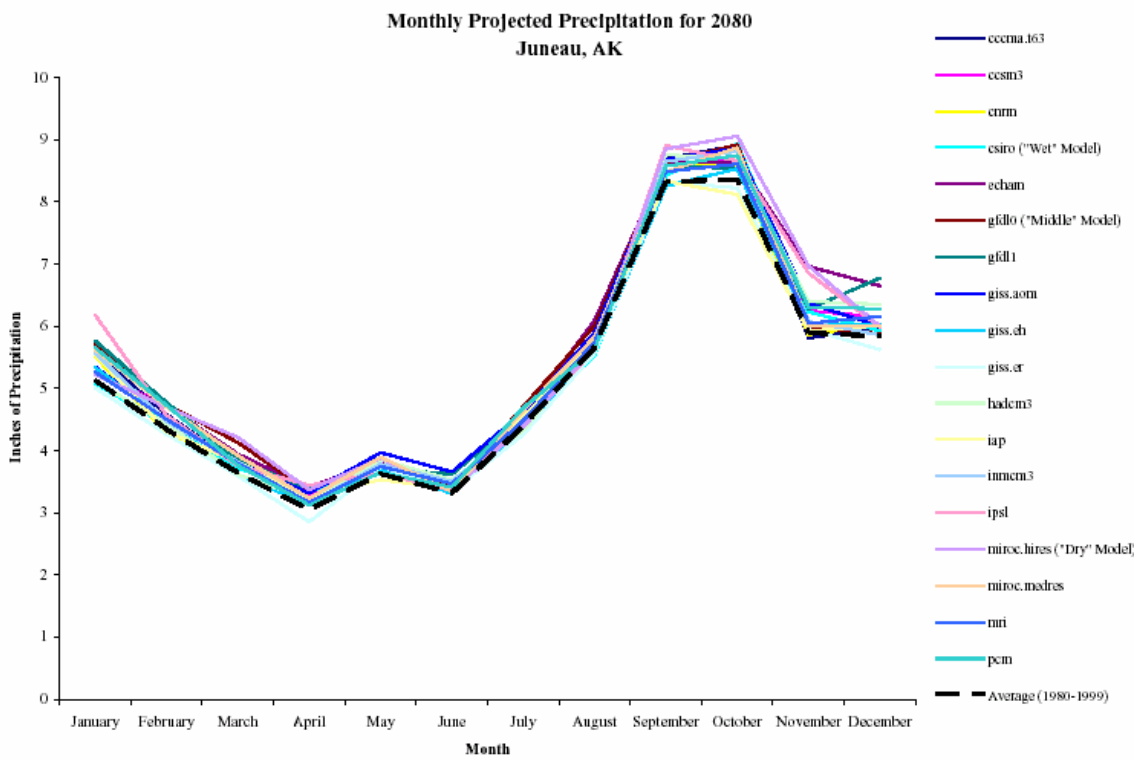
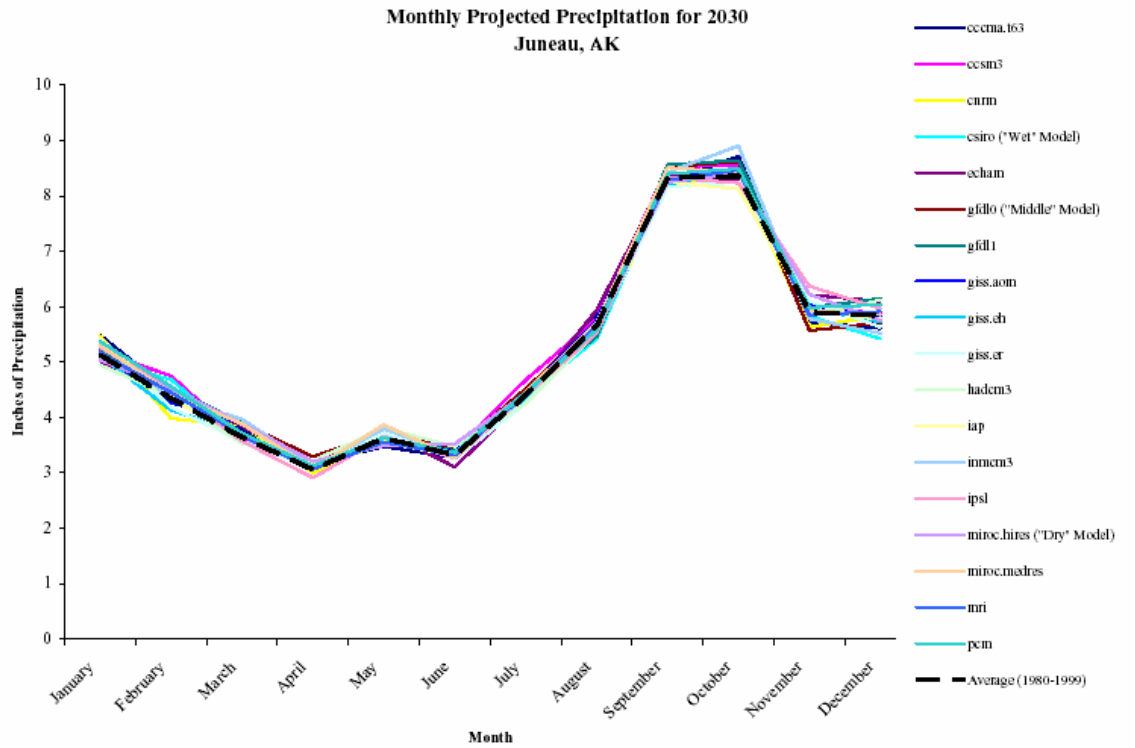


Figure 19. Average monthly precipitation for Juneau (dashed lines) and precipitation predicted for Juneau in the years 2030 (upper panel) and 2080 (lower panel) by 18

climate models (colored lines). Model outputs provided by Lawrence Livermore National Laboratory (PCMDI Collection), National Center for Atmospheric Research, and the Institute of Social and Economic Research at the University of Alaska Anchorage.

## **Climate Change Impacts**

### **Impacts on Juneau's Hydrologic Resources**

Climate change is already affecting the physical landscape in Alaska. The most obvious effects on Alaska's hydrologic resources (streams, rivers, lakes, and wetlands) are changes in the temporal and spatial extent of permafrost, snow cover, glaciers, and lake ice cover (Oswood *et al.* 1992). The most dramatic loss of glacial ice in Alaska since the end of the Little Ice Age occurred in Glacier Bay. Within the west arm of the bay, glaciers have retreated more than 60 miles and lost nearly 1 mile in thickness (Figure 20). As a result, less than 30% of Glacier Bay National Park is now covered by glaciers. The mass balance record for the Lemon Glacier near Juneau is one of the longest in North America, and it indicates a dramatic loss of volume in recent decades. During the period 1953-1998, the glacier thinned nearly 81ft and retreated more than 2600 ft (Miller and Pelto 1999).

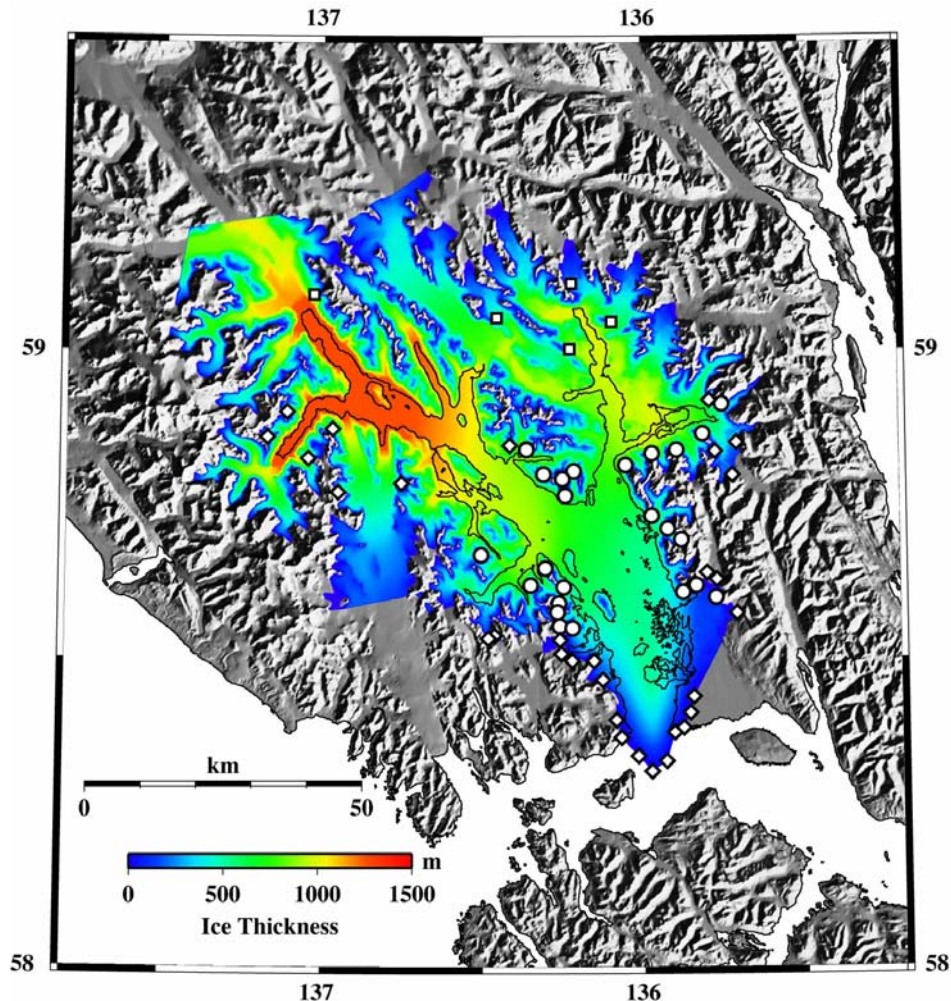


Figure 20. Decreases in glacial ice thickness in Glacier Bay since 1750. Some areas of the Upper West Arm of the Bay lost more than 4,875 ft of ice during that time. Figure modified from Chris Larsen, University of Alaska Fairbanks Geophysical Institute, [http://www.giseis.alaska.edu/Input/chris/gb\\_lia\\_icethick.jpg](http://www.giseis.alaska.edu/Input/chris/gb_lia_icethick.jpg)

Currently, the majority of glaciers in southeastern Alaska are thinning and retreating. Rates of glacier thinning now exceed 10 ft per year at lower elevations (Figure 21; Larsen *et al.* 2005; Larsen *et al.* 2007). Moreover, rates of glacial ice loss appear to be increasing in recent decades (Arendt *et al.* 2002). Recent losses of glacier ice appear to be associated with climate warming rather than changes in precipitation regimes (Arendt *et al.* 2002; Motkya *et al.* 2002).

Despite ongoing glacial retreat, some projections suggest that increasing winter temperatures in high-latitude latitudes, and a resulting intensification of the hydrologic

cycle, may lead to greater snow accumulation (Mayo and Trabant 1984, Mayo and March 1990). Indeed some southeastern Alaska glaciers, including the Carroll, Johns Hopkins, Lamplugh, Reid, Margerie, Brady, and Grand Pacific glaciers in Glacier Bay (Hall *et al.* 1995) and the Taku glacier (Pelto and Miller 1990; Miller *et al.* 2003) have shown periods of advance during the latter half of the 20<sup>th</sup> century. It also is important to note that the effects of climate change on southeastern Alaska glaciers may be very different for tidewater glaciers in contrast to glaciers with grounded termini. Glaciers that terminate at tidewater typically follow their own cycles of advance and retreat that are often independent of short-term changes in regional climate. For example, Hunter and Powell (1993) found that terminus dynamics at the Grand Pacific and Muir Glaciers in Glacier Bay are controlled by morainal bank sediment dynamics and concluded that these tidewater glaciers are insensitive to climate forcing. Regional climate warming, however, does appear to be affecting non-tidewater glaciers in southeastern Alaska, the majority of which are receding.

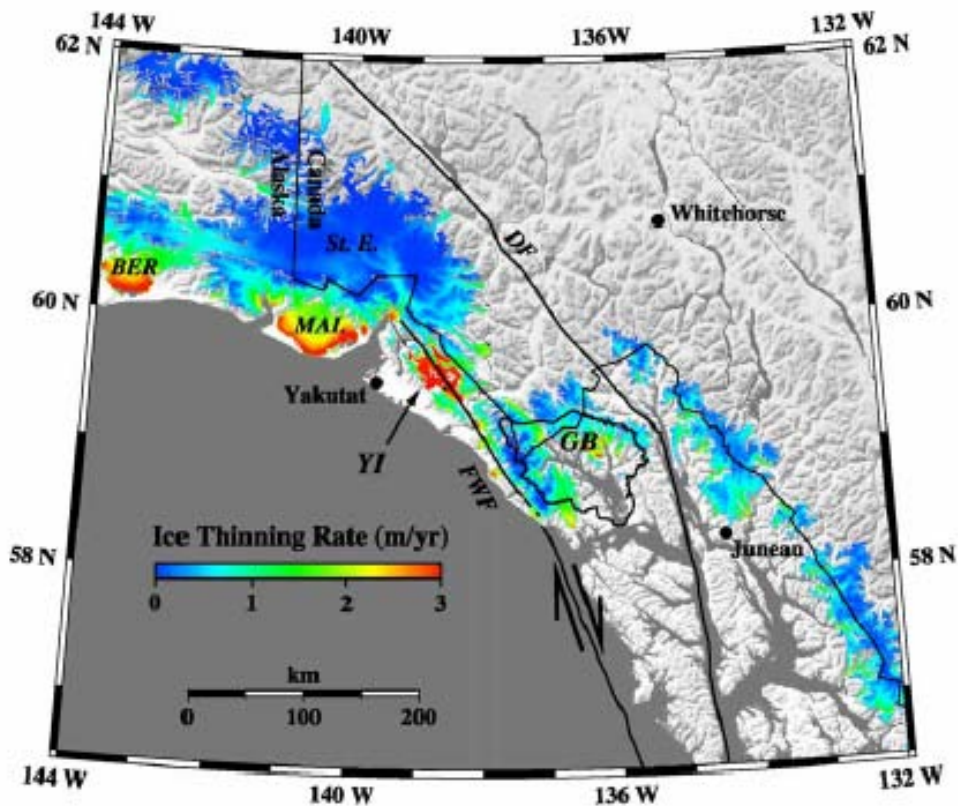


Figure 21. Current rates of glacier ice thinning in southeastern Alaska as measured by laser altimetry. Ice in lower elevations and the around the Yakutat Icefield is thinning most rapidly. The Glacier Bay Little Ice Age Icefield is outlined. FWF depicts the location of the Fairweather Fault. Figure from Larsen *et al.* 2005.

The dramatic thinning of glaciers may alter the landscape of southeastern Alaska. Rapid glacier wastage in the region is reflected in extreme rates of glacio-isostatic rebound, a rising of the earth where it formerly was depressed by the mass of ice. Total land surface uplift in Juneau since the late 18th century has been estimated at 10.5 ft, which corresponds with the 0.5 inch/yr decrease in sea level evident in local tide gauge records (Motkya 2003).

### **Impacts on snow cover**

The depth and duration of snow cover are changing in the Juneau Area. Because the average winter temperature in Juneau is close to the freezing point of water (32°F), snow cover is very sensitive to small changes in temperature, particularly at lower elevations where the warming influence of the ocean is greatest. Winter climate in Juneau has changed dramatically since continuous records began to be kept at the airport in 1943. Here, winter is defined as November through April (e.g., winter 2006 is from November 2005 through April 2006), because these are the months during which Juneau regularly receives snowfall at sea level. Average winter snowfall at the airport decreased by almost 1.5 ft, from 109 inches to 93 inches between 1943 and 2005 (Figure 22). During the same period, average winter temperature has risen by approximately 2°F and average winter precipitation (rain plus snow reported as inches of liquid water) has increased by approximately 2.6 inches (Figure 22). Thus, the decrease in snowfall at sea level appears to be driven by climate warming rather than a decrease in winter precipitation. Since the early 1980s, the average winter temperature increased above the freezing point of water (Figure 22).

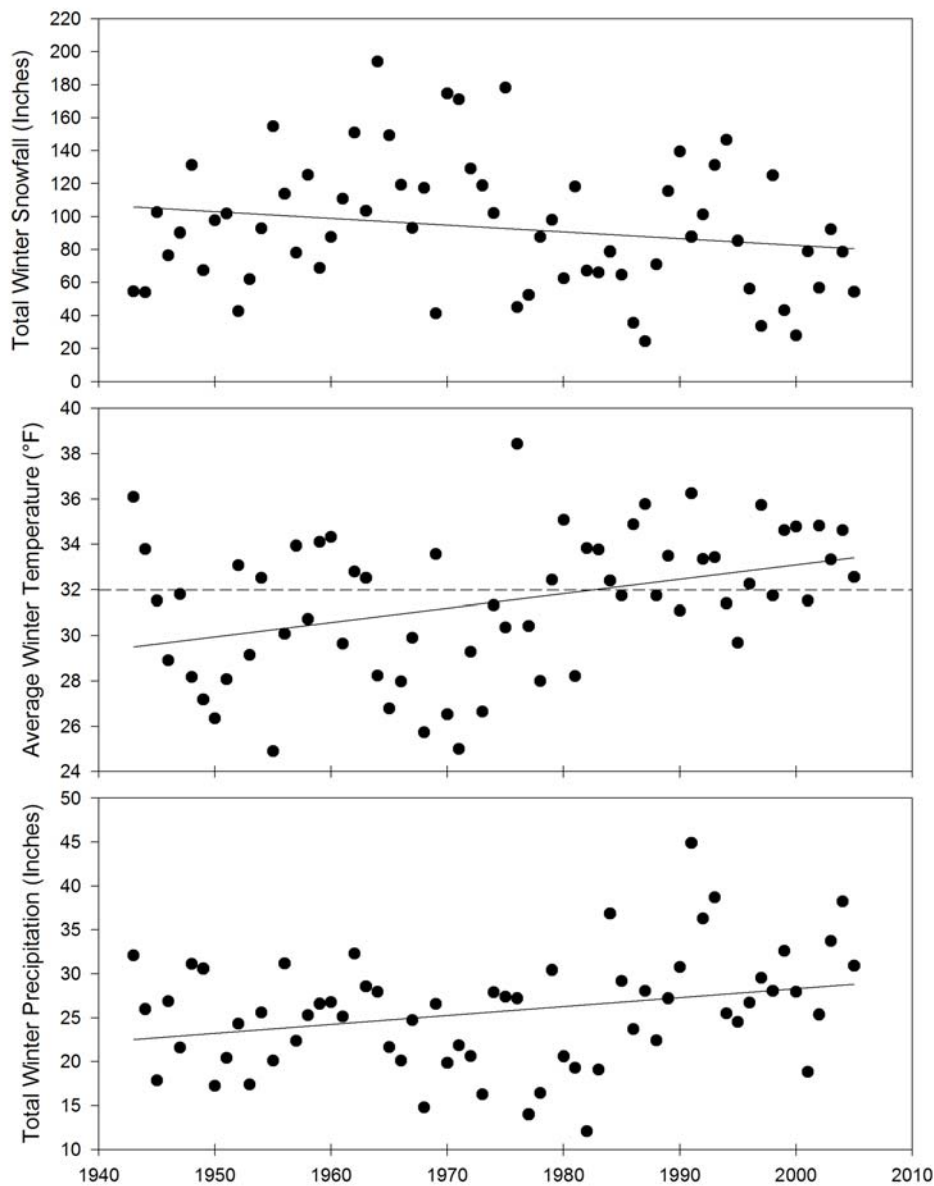


Figure 22. Average winter (November - April) snowfall (top), temperature (middle), and precipitation (bottom) at the Juneau Airport from 1943 to 2005. The linear regression for snowfall is not significant at the 95% confidence level ( $p=0.13$ ). The linear regressions for temperature ( $p<0.01$ ) and precipitation ( $p=0.02$ ) are both significant at the 95% confidence level.

Snowfall has been consistently below average since the mid-1970s with the exception of a period in the early 1990s (Figure 23). Similarly, winter temperature and precipitation shifted in the mid-1970s to early 1980s toward warmer and wetter than the long-term

average (Figure 23). The observed shift in winter time climate in Juneau corresponds well with shifts in the Pacific Decadal Oscillation (PDO) during the same time period. The PDO is a long-lived (20-30 years) El Niño-like pattern of Pacific climate variability that has warm and cool phases. The warm phase of the PDO is typified by onshore flows and warmer sea surface temperatures in the Gulf of Alaska, while the cool phase is typified by offshore flows and colder sea surface temperatures in the Gulf of Alaska. The North Pacific was in a “cool” PDO regime from 1947-1976 and was in a “warm” PDO regime from 1977 through at least the mid 1990s.

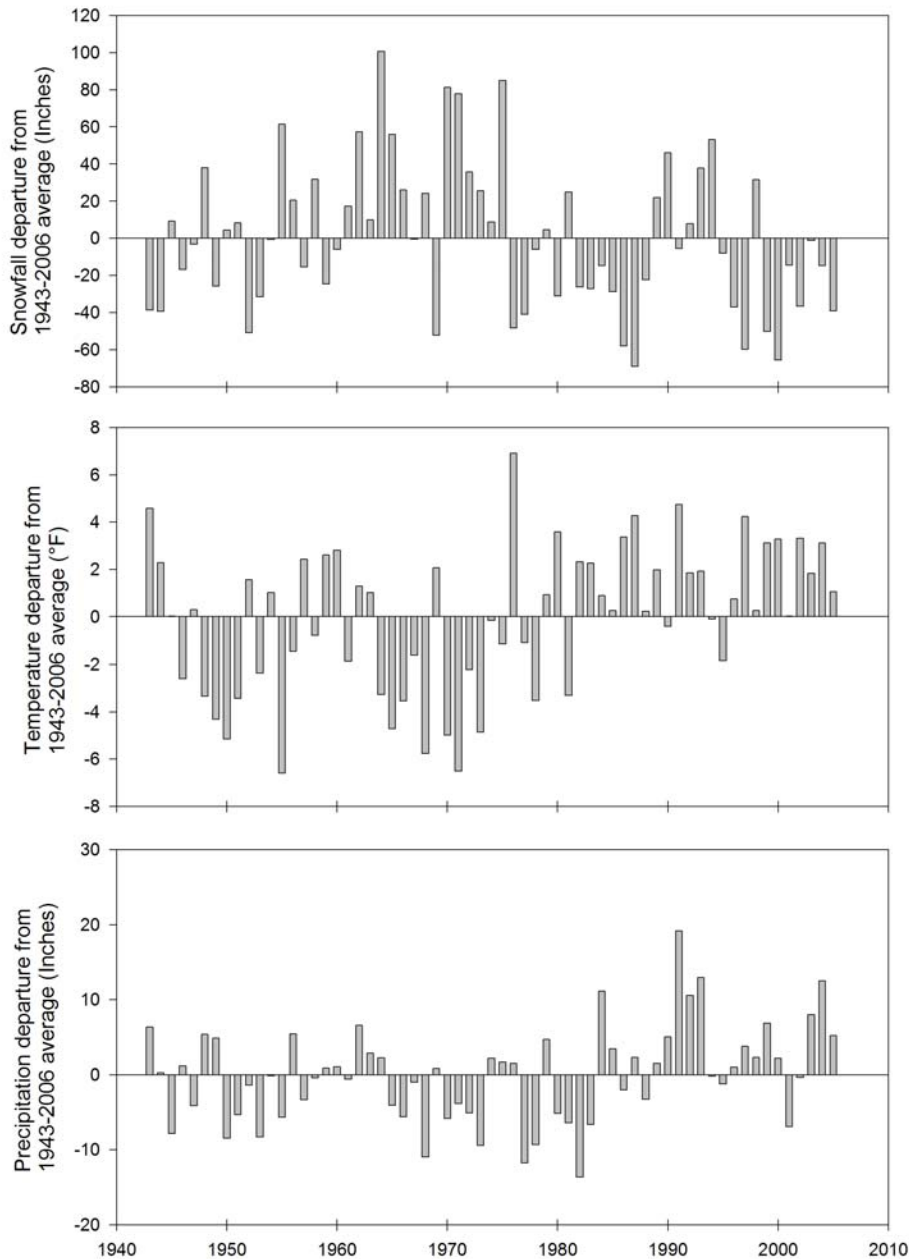


Figure 23. Departure from the long term (1943-2006) average for winter snowfall (top), temperature (middle), and precipitation (bottom) at the Juneau Airport.

The trend toward warmer, rainier winters at sea level in Juneau during recent decades is likely due in large part to both the recent predominance of the warm phase of the PDO and to global climate warming, the effects of which are more pronounced at higher latitudes. The trends in climate appear to affect late winter and early spring snowfalls in

Juneau most strongly. Since 1975, average snowfall in March and April in Juneau has decreased significantly; however, there has not been a significant change in average snowfall in other months in which snow typically falls at sea level (Figure 24). The change in snowfall regime is most pronounced in April, a month in which snowfall at sea level has become rare for Juneau. Snowfall data in Juneau are consistently collected only at sea level, so it is difficult to evaluate how changes in climate are affecting snowfall at higher elevations. The negative mass balance for most local glaciers suggests that snowfall at higher elevations is also decreasing. It is possible, however, that a warmer, wetter climate will result in an increase in snowfall at the highest elevations within the CBJ (such as the upper reaches of the Juneau Icefield) where winter temperatures are consistently well below the freezing point of water. Because much of the CBJ and southeastern Alaska are located within a few thousand feet of sea level, depth and duration of snow cover at lower elevations most likely will continue to decrease as the climate warms.

The areas of southeastern Alaska most at risk to lose their winter snow cover entirely are those areas near sea level that presently have low levels of snow accumulation (Figure 25). Because of uncertainty about the effects of climate change on the snowfall at higher elevations, it is difficult to predict how the urban avalanche danger within CBJ may be affected by a warming climate. A decrease in snowfall within the 0-3000 ft elevation range would lower the risk of avalanche danger for CBJ. Increased snowfall at higher elevations (above 1000 ft), however, coupled with more frequent shifts between warm and cold temperature regimes during the winter could actually increase avalanche danger for downtown residents and backcountry travelers.

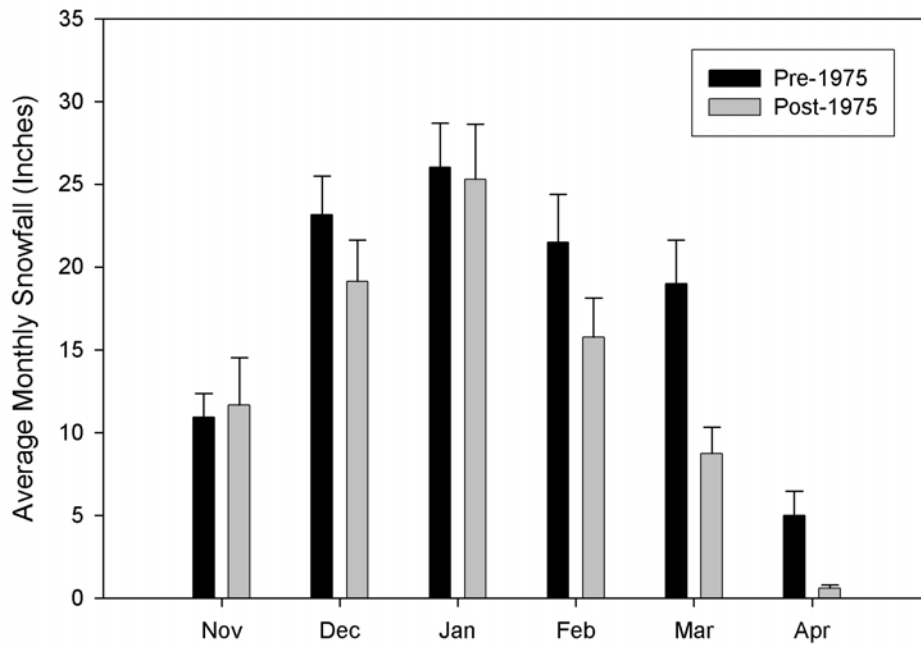


Figure 24. Average monthly snowfall ( $\pm 1$  standard error) at the Juneau airport for winter (November-April) months before and after 1975. Significantly less snow fell during March and April in the recent years ( $p < 0.01$  for both comparisons). There has not been a significant change in snowfall in the other months (November-February).

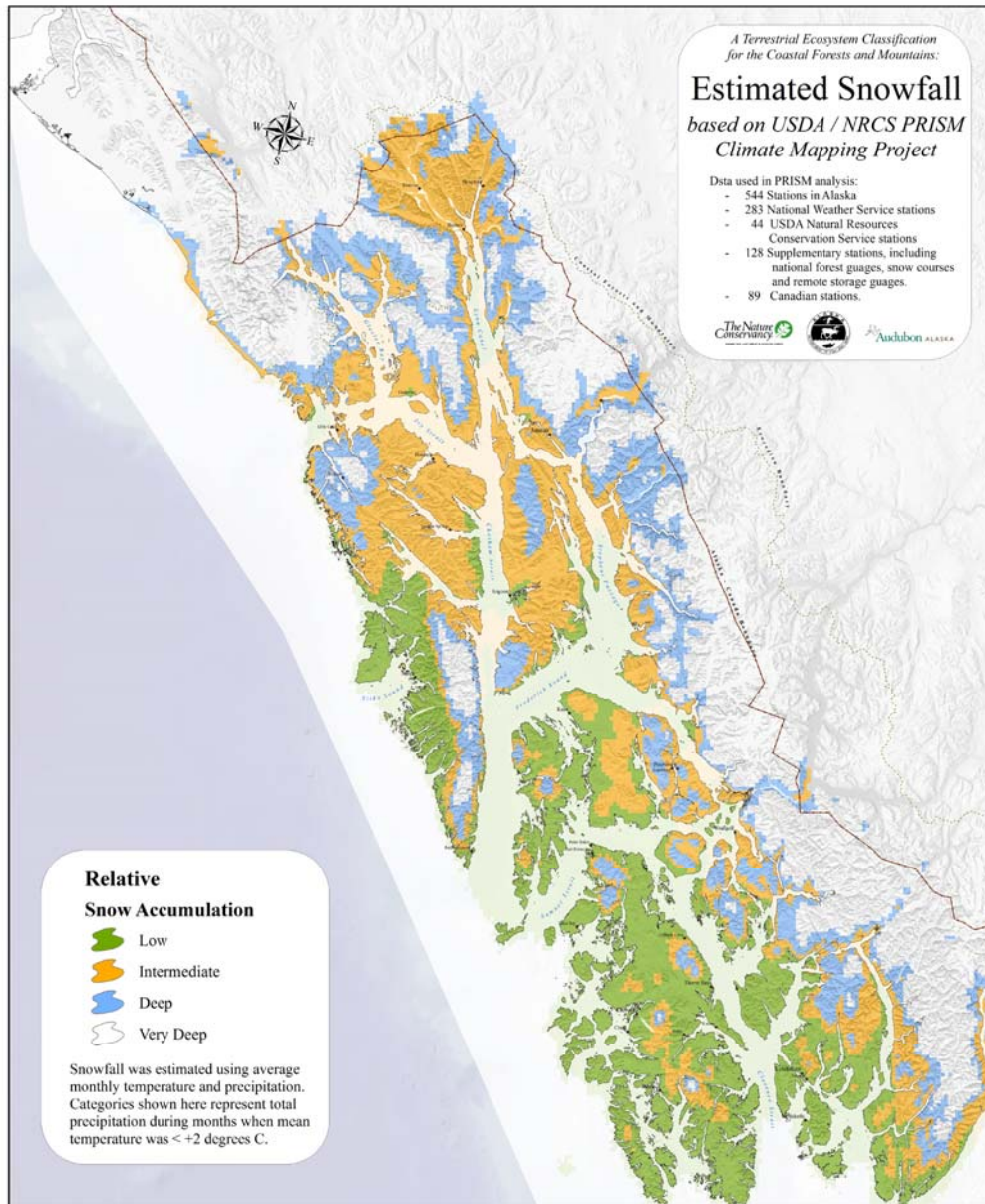


Figure 25. Model of relative snow accumulation in southeastern Alaska. Figure courtesy of Dave Albert, The Nature Conservancy, Juneau, AK.

### Impacts on sea level in Juneau

In coastal southeastern Alaska, the rapid retreat and thinning of glaciers resulting from climate change (see glaciers section) is contributing to extremely high rates of relative sea level change. As the mass of ice in this region decreases and diminishes the overburden on the earth's crust, the earth's crust slowly rebounds and causes a relative

*decrease* in sea level height. This isostatic rebound is occurring over a wide region between Yakutat and the CBJ (Sauber *et al.* 2000, Larsen *et al.* 2004). The entire north Gulf of Alaska coast also contains active fault systems associated with the juncture of the Pacific and North American tectonic plates. Thus, active tectonic deformation of the southeastern Alaska region is also a possible source of uplift. Seismic activity in southeastern Alaska is high, with the Fairweather Fault running through the region. Five earthquakes of magnitude 7.0 or higher have been recorded around Yakutat within the last century (City of Yakutat 2005). The effects of tectonic activity on land surface uplift, however, are thought to be minor in contrast to isostatic rebound from the loss of glacial ice (Larsen *et al.* 2004).

Current rates of land surface uplift in the northern portion of southeastern Alaska are among the highest ever recorded. Recent measurements made with global positioning systems (GPS) have recorded rebound rates of up to 1.2 inches per year in Glacier Bay and 1.3 inches per year centered over the Yakutat Icefield to the northwest (Figure 26; Larsen *et al.* 2004). Rates of uplift in the Juneau area average about 0.5 inches per year (Figure 26). In contrast, global sea level rose approximately 0.04 – 0.08 inches per year during all of the 20<sup>th</sup> century. The uplift is dramatically altering the landscape of the northern panhandle. Surveys of raised shorelines in northern Lynn Canal and Glacier Bay have recorded relative sea level changes of more than 15 ft since the end of the LIA (Figure 27). In the Juneau area, uplift has raised shorelines as much as 10 ft during this period.

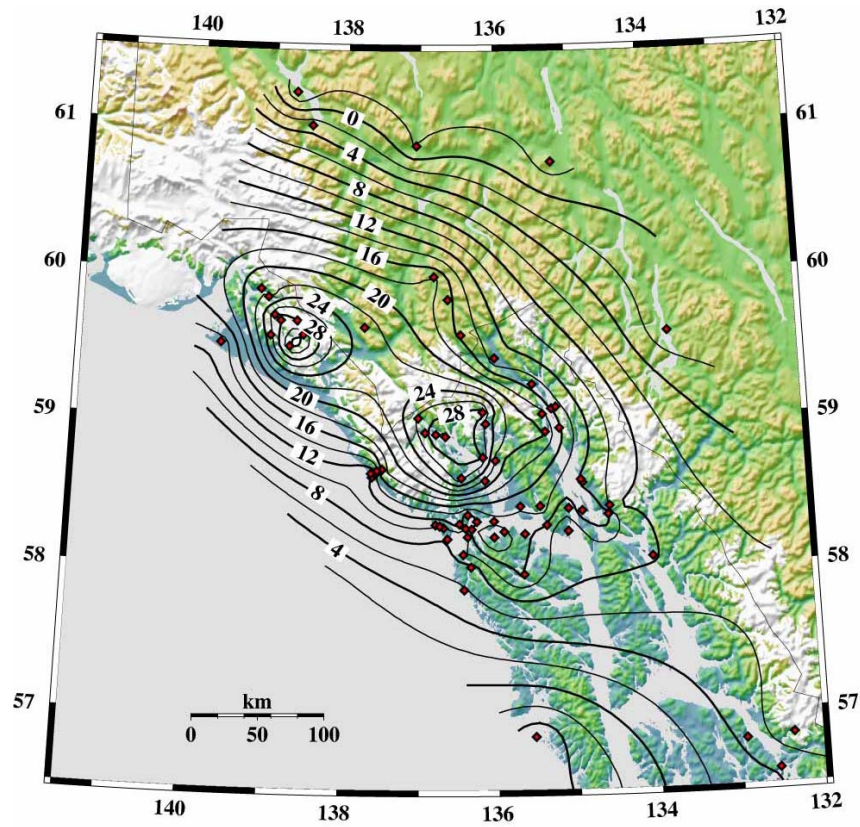


Figure 26. Current land surface uplift rates (mm/yr; 25.4 mm = 1 inch) in southeastern Alaska from GPS measurements. Modified from Chris Larsen, University of Alaska Fairbanks Geophysical Institute (<http://www.giseis.alaska.edu/Input/chris/gpsuplift.jpg>).

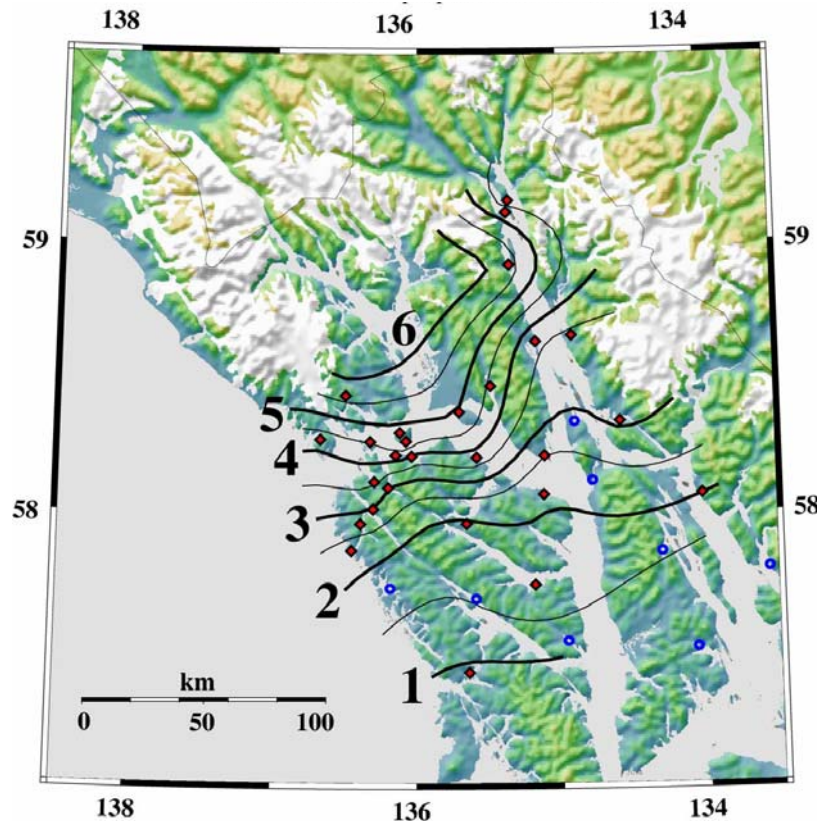


Figure 27. Relative sea level decrease estimated from raised shorelines (meters, 1 m = 3.3 ft) in southeastern Alaska since the end of the Little Ice Age. Contour interval is 0.5 m. Modified from Chris Larsen, Geophysical Institute, University of Alaska Fairbanks (<http://www.giseis.alaska.edu/Input/chris/shorelinecontour2.jpg>).

Over the next century, rates of land surface uplift within the CBJ likely will remain steady and possibly even increase as a result of continued glacier ice loss. Thus, the relative sea level *decrease* within CBJ as a result of isostatic rebound can be conservatively estimated at 3.9 ft over the next century. At the same time, global sea level is rising as a result of two factors: 1) the melting of glaciers and ice sheets that is causing the mass of ocean water to increase and 2) the warming of ocean waters that is causing the volume of the ocean to increase through thermal expansion. The best estimates for global sea level increase in the next century range from 0.3 ft to 3.0 ft (Figure 28). Under any of several sea level rise scenarios (Figure 28), the CBJ should experience a relative *decrease* in sea level of between 1.0 and 3.6 ft over the next century as a result of the combined effects of sea level rise and land surface uplift.

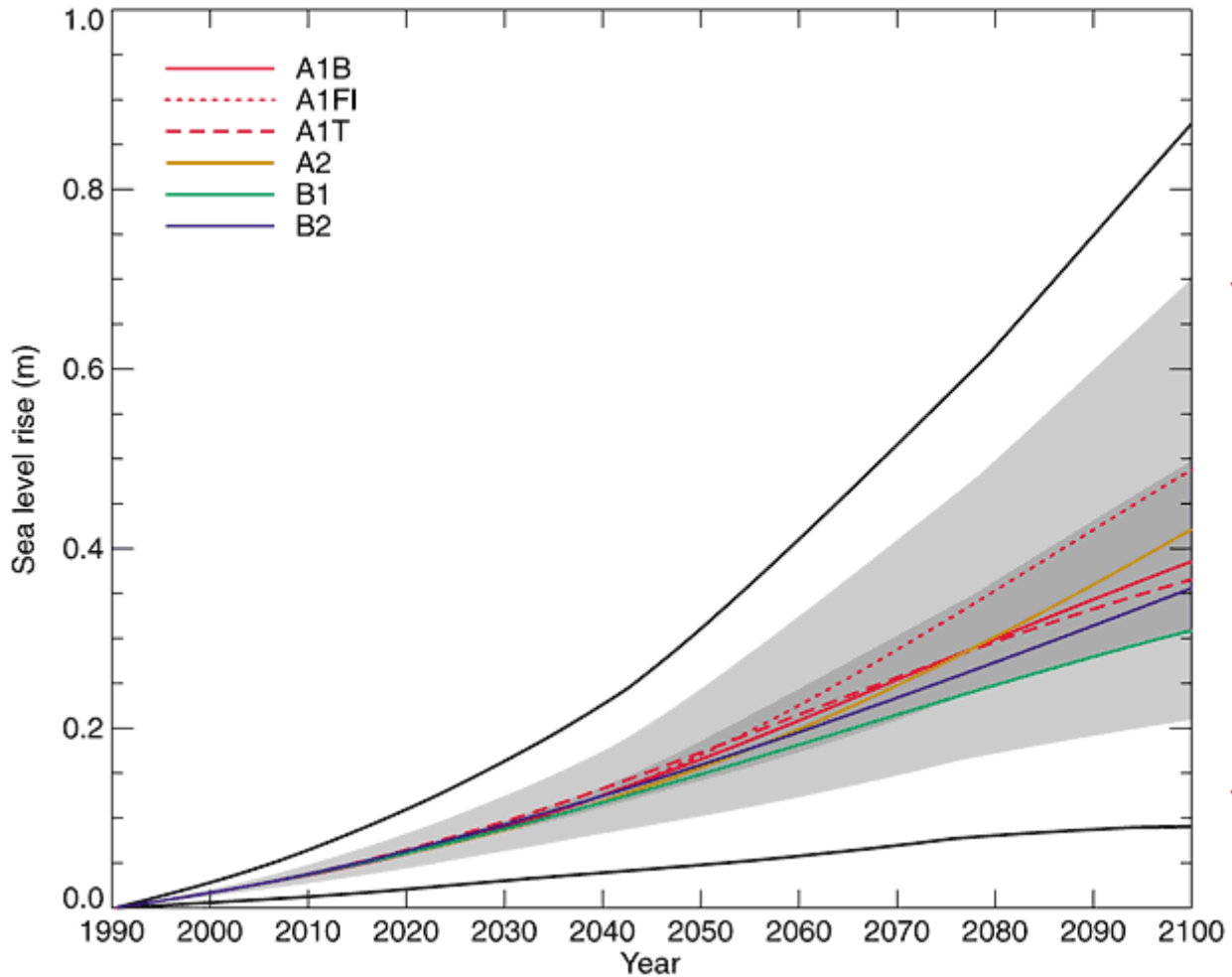


Figure 28. Modeled global average sea level rise 1990 to 2100 based on a variety of greenhouse gas emission scenarios. Figure from the Intergovernmental Panel on Climate Change (IPCC) 2001 report ([http://www.grida.no/climate/ipcc\\_tar/wg1/429.htm#1151](http://www.grida.no/climate/ipcc_tar/wg1/429.htm#1151)).

Glacio-isostatic rebound will potentially affect the stability of the major tectonic faults (Fairweather and Denali) running through southeastern Alaska. Indeed, the release of overburden stress caused by glacier thinning appears to be increasing number of earthquakes in southeastern Alaska (Sauber and Molnia 2004). Uplift in southeastern Alaska has precipitated changes in the composition and location of key vegetation types, which in turn, caused dramatic changes in fish and wildlife habitat (Mills and Firman 1986). For example, in some areas of southeastern Alaska, high marsh communities dominated by grasses have replaced the sedge-dominated low marsh communities

(Armstrong *et al.* 2004). Migrating birds such as pipits and longspur favor high marsh communities, while low marsh communities are nutritionally crucial for waterfowl such as Vancouver Canada Geese (Armstrong *et al.* 2004).

In addition to changes in habitat, these ongoing shifts in the elevation of the land surface also have implications for the hydrology of small coastal streams, many of which support salmon populations. One stream in the Juneau area which appears to be impacted by uplift is Duck Creek in the Mendenhall Valley. Water table levels in the Mendenhall Valley have been decreasing at approximately 1.5 in/yr during the last two decades. This decrease in water table elevation is thought to be due to land surface uplift in combination with down cutting along the Mendenhall River channel (Neal, unpublished data; Walter *et al.* 2004). The lowering of the water table elevation appears to be affecting the hydrology of streams within the valley. For example, during low flow periods of the last decade, Duck Creek has experienced a steady decrease of approximately 0.11 ft<sup>3</sup>/s/yr (Walter et al 2004). As a result, the lower reaches of Duck Creek now often run dry in the spring and summer. The hydrology of Jordan Creek may be similarly impacted. Because other regions of southeastern Alaska are currently experiencing greater uplift rates than Juneau, it is possible that other coastal streams fed by groundwater may be experiencing a reduction in low flows over time which may make them impassable for fish, limiting the range of certain anadromous stocks. The US Geological Survey office in Juneau is currently preparing a report on recent changes in the ground-water hydrology of the Mendenhall Valley resulting from glacial recession and land surface uplift (Edward Neal, USGS Juneau Office, personal communication, 2006).

In Glacier Bay, National Park Service staff recently noted an increase in the growth of aquatic plants in the East Alsek River, which is changing water flow and sedimentation patterns (Chad Soiseth and Bill Eichenlaub, National Park Service, Glacier Bay, personal communication, 2005). These plants grow quickly and form dense clusters, which can trap organic material and decrease water flow rates. The increased abundance of these plants in the East Alsek River is hypothesized to result from the lack of periodic flooding of the East Alsek by the Alsek River, which is believed to be due to uplift, subsequent

river downcutting, and elevation of the flood plain (Chad Soiseth, NPS-GLBA, personal communication, 2005). The NPS is analyzing and documenting these vegetative changes (Bill Eichenlaub, NPS-GLBA, personal communication, 2005).

### **Biological responses**

Temperature and moisture are among the most pervasive features of the physical environment in their influence on the distribution and abundance of organisms. Changes in those climate variables will directly and indirectly effect the composition of the terrestrial and marine ecological communities surrounding Juneau. The Intergovernmental Panel on Climate Change has concluded that the risk of extinction will be high for 20 – 30% of all plants and animals if global air temperatures increase 2.7 – 6.8°F (Adger 2007). Direct effects will be realized when the temperature or moisture limits of a species are exceeded. Indirect effects will include the response of organisms to changes in the prevalence or presence of other species as competitors, prey, predators, or parasites.

#### **Terrestrial ecosystem**

Three million years ago, during the middle of the Pliocene (when modern plants and animals appeared), temperatures were 6-9°F warmer than today, and oceans were 80 ft higher than today (Hansen *et al.*, *in review*; Dowsett *et al.* 1994). It was the warmest interglacial period on record. The Holocene, which began 12,000 yr before present, has been an era of climatic stability and a period during which civilization flourished. Environmental stability has been important in the evolution of agriculture and, hence, civilization.

Biological responses to climate change are scalar and depend on the magnitude and direction of change. The greater the magnitude and rate of change, the greater will be the adverse or beneficial effects (IPPC 2001a, in Inkey *et al.* 2004). Juneau's climate has been dynamic since the end of the last major ice age, some 12,000 years ago, which exposed new landscapes as the ice sheets retreated. Evidence of past climate variability

comes from pollen profiles in lake sediments, variation in tree growth from tree rings, and most recently, through interpretation of daily data from weather stations.

Pollen profiles demonstrate the occurrence of different tree species in southeastern Alaska during the last 12,000 years, indicating a variable climate even during a period considered geologically stable. For example, pine forests dominated Juneau landscapes for about 1,000 years and were subsequently replaced by spruce and hemlock trees as the climate became cool and wet. Although local ecosystems appear relatively stable, they are of recent origin and are composed of shifting assemblages of plant and animal species. New landscapes are still being exposed by a combination of retreating glaciers and isostatic rebound. Weather records, which date to 1881 at various stations in southeastern Alaska, show a trend of warming spring months, longer growing season, and reduced snow pack. Important to terrestrial organisms is the fact that Juneau's average winter temperature has warmed to above 32°F, the threshold of precipitation falling as either snow or rain. Mild warming may result in more rain and reduced winter and spring snow pack at lower elevations.

The direction and magnitude of change in temperature and precipitation has important effects on terrestrial environments. Using global climate change models developed by the Canadian Climate Center (CGCM1) and the Hadley Centre (HADCM2SUL; Mitchell *et al.* 1995; Johns *et al.* 1997), Bachelet *et al.* (2005) simulated the response of ecosystems to climatic variability in Alaska. Overall, average annual temperature increases predicted by Bachelet *et al.* (2005) for the end of the century range from 9 to 14.4 °F. Temperature increases over continents should be 1.5 times larger than over oceans (IPPC 2001c); compensating for the marine influence results in a 6 to 9.6°F annual temperature change increase for southeastern Alaska. Oscillation around the average is expected, but the trend is upward. The ability of organisms to adapt will depend greatly on how quickly average temperatures increase in the coming century.

## Soils

Approximately two-thirds of terrestrial carbon is stored in soils. As the climate changes, much of that carbon is expected to be transported from soils to the oceans and the atmosphere (Mulholland and Kuenzler 1979). Northern temperate and boreal ecosystems dominate the worldwide storage of carbon due to the extensive peat lands with deep organic soils. These deposits are not mapped as extensively, however, as in agricultural areas, and our knowledge of the amount of carbon stored in northern soils is imprecise. Soils in southeastern Alaska contain an estimated 1.2 billion metric tons of carbon (Alexander *et al.* 1989, Leighty *et al.* 2006). That estimate, however, excludes the deep, unfrozen peat deposits found in the organic soils of the region, and may underestimate actual carbon stored in forested soils (Harrison, *et al.* 2003). Also, current survey methods may underestimate the carbon storage in southeastern Alaskan soils (D'Amore and Lynn, 2002; D'Amore in prep.).

Carbon stored in soils may be lost in gaseous forms through oxidation of soil organic matter and by way of associated increases in dissolved organic carbon in surface water. The potential to transfer soil carbon to the atmosphere by these means is high in southeastern Alaska where temperatures are mild and precipitation is abundant. Increasing temperature leads to increased oxidation of soil organic matter, and increased rainfall increases the export to streams of dissolved material including carbon. Recent increases in dissolved organic carbon in streams in Great Britain have been attributed to increased oxidation and production of dissolved organic carbon in wetland soils (Hope *et al.* 1994).

Organic soils are known to be significant sources of dissolved organic carbon for streams in northern forested ecosystems (Mulholland and Kuenzler 1979). Further measurements of organic soils need to be linked with transport studies to enhance our understanding of carbon export in southeastern Alaskan forested watersheds.

### Vegetation

Warming and increases in precipitation will favor some plants but may stress others. Solar energy is converted in to plant matter via one of two photosynthetic pathways, C<sub>3</sub>

and C<sub>4</sub>. Trees and certain shrubs that use the C<sub>3</sub> pathway will benefit more from warming than will grasses and other shrubs that use the C<sub>4</sub> pathway (Wheaton *et al.* 1987). Longer growing seasons with warmer temperatures likely will result in faster growth. Those conditions also will favor more rapid decomposition and a transition of bog and forested wetlands to more productive forests with larger stature trees. New habitats will be colonized by plants as glaciers recede and inter-tidal areas are uplifted. Timberline species already are advancing upslope as documented by alder colonization on Mt. Juneau and elsewhere (R. Carstensen, Discovery Foundation, Juneau, Alaska, personal communication).

Climate is the primary factor controlling plant distribution, and small changes in annual temperature can have large ecological (and economic) impacts. Climate changes are predicted to eliminate mountain hemlock and alpine tundra from some portions of British Columbia (Hamann and Wang 2006). Conditions suitable for conifer trees will expand northward at a rate of 60 miles per decade, although there will be lags before the trees actually colonize the new habitats (Hamann and Wang 2006).

A warmer climate will stress some tree and plant species that are not well adapted to new conditions. Sugar maple (*Acer saccharum*) is expected to disappear entirely from the U. S (Inkley *et al.* 2004). Warmer conditions frequently favor insects, some of which attack forest trees and under story plants with devastating effect.

Plants respond to specific environmental cues to initiate processes such as hardening in the fall and dehardening in the spring. When the cues change, vital processes, such as the timing of cold hardiness, can be altered leading to plant mortality. The widespread decline of yellow cedar in southeastern Alaska and British Columbia appears to be due to freezing deaths resulting, counter-intuitively, from warming temperatures (Juneau Forestry Sciences Laboratory, unpublished data). Warming spring temperatures have lead to premature de-hardening of the trees and premature snow melts. Without the insulating snow cover, the tree roots are injured in subsequent cold weather Hennon *et al.* (2005).

The climate of southeastern Alaska and British Columbia was favorable for the commercially valuable yellow-cedar until the end of the Little Ice Age in the mid 1800s.

Longer term effects of climate change will result in both range extensions and retractions. More southerly species, such as western red cedar and Douglas-fir, are predicted to migrate northward (Hamann and Wang 2006). Perhaps, the greatest change to forests surrounding Juneau will result from the introduction of fire. The hemlock and spruce dominated forests of coastal southeastern Alaska and British Columbia are not adapted to fire, and warmer weather, along with lightening as a source of ignition, will result in fire becoming a major disturbance force disrupting the rainforest environment.

Increasing temperatures also will result in cold limited species extending their range to higher elevations. Air temperatures typically decrease by 3°F with every 1,000 feet gained in elevation. Given an expected average annual temperature increase of 6°F to over 9°F degrees by the end of the century, temperatures currently experienced at sea level will advance 2,000 to 3,000 feet upslope. Today's average snow conditions at the Eaglecrest ski area lodge will be experienced at the top of Hooter Lift (about 500 ft higher) in 16 to 25 years and at the top of Ptarmigan Lift in about 65 years.

Two common conifers in southeastern Alaska, Sitka spruce and western hemlock, are expected to move upslope as the climate warms. Mountain hemlock, which grows at elevations above Sitka spruce and western hemlock but below tundra, also will move upslope, and may eventually disappear as predicted for British Columbia (Hamann and Wang 2006). Mountain hemlock also occurs in wetlands and may persist there while being extirpated in other locations. Models predict that 75%-90% of the area that was tundra in 1922 will be replaced by boreal and temperate forest by the end of the 21<sup>st</sup> century (Baschelet *et al.* 2005). By then, we can expect lower elevation alpine/tundra habitat in southeastern Alaska to be largely replaced by shrubs and trees. Populations of species strongly associated with alpine/tundra ecosystems will similarly be reduced in number, fragmented, or eliminated as temperatures increase.

As precipitation in southeastern Alaska shifts toward increased rain and less snow, more water will run off the landscape rather than being stored. Meadows and bogs may dry as a result. In western Canada, there has been a significant decrease in aspen growth due to decreased availability of moisture over nearly a half century (Hogg *et al.* 2005), and continued warming is predicted to lead to a 43% decrease of aspen in British Columbia (Hamann and Wang 2006). At the same time, wetlands may become more forested and productive.

The ability of plant communities to adapt to climate change will be challenged by the rapid rate of the change. Unlike animals, plants cannot move as individuals and distributional changes are slower. For plants to follow favorable temperatures to higher elevations, they will have to adapt to steeper slopes with different soils, moisture conditions, and bacterial communities. Species that cannot adapt rapidly enough will become locally extinct. At the same time, plants presently adapted to the highest elevations will not have new habitats above to which they can adapt and also face local extinction.

### Insects

Warmer temperatures will expand the distribution of many insects and enhance their reproductive and survival rates. Insects that infect plants and animals will become more common in the CBJ.

The spruce beetle (*Dendroctonus rufipennis* [Kirby]) spread through the Kenai Peninsula killing 80 percent of the spruce trees during the 1990's and continues to kill trees there today; it was the largest tree die-off ever recorded in North America (Inkley *et al.* 2004). Over 2 billion board feet of saw-timber was lost. The reproductive rate of spruce beetles depends on temperature. A complete life cycle typically requires two years, three years in cold conditions, and 1 year in warm conditions. Warm temperatures in the 1990's allowed the beetle's life cycle to be completed in a single year and over-wintering beetle survival increased its population size. Growth of the spruce beetle population was further enhanced by a drought that stressed the trees and rendered them more susceptible to

attack (Berg *et al.* 2006). A beetle induced die-off of white spruce (*Picea glauca*) trees in the Copper river basin, improved habitat for some birds but reduced the densities of the ruby-crowned kinglets (*Regulus calendula*) and red squirrels (*Tamiasciurus hudsonicus*) (Matsuoka *et al.* 2001).

Western balsam bark beetle (*Dendronctonus confusus* Swaine) killed subalpine fir (*Abies lasiocarpa* Hook., Nutt.) in 2002 in the Skagway river drainage. The northern-most extension of Balsam bark beetles is now in the Taiya Inlet 1.5 km south of Skagway (Wittwer, 2002). In 2005, 3.5 million acres of subalpine fir were infested in British Columbia (Westfall, 2005). As with spruce bark beetles, reproductive rates of western Balsam bark beetles are enhanced by warmer temperatures. Over winter survival also increases with warmer temperatures (Williams and Liebhold 2002). Models predict that beetle outbreaks will occur nearly 100 ft higher for every 1.8°F increase in temperature (Williams and Liebhold 2002).

Sitka spruce trees survived infection by Sitka spruce aphids until temperatures increased over-winter survival rates of the aphids (Lynch and Schultz 2006). The affected area near Sitka and the frequency of aphid outbreaks increased after 1970, probably due to shorter and warmer winters. Since 1940, mean annual midpoint temperatures (halfway between the minimal and maximal temperatures) at Sitka increased 3.6°F. The minimal winter temperature increased by 10.8°F and there are 20 fewer days with below-freezing temperatures per year. Spruce aphid mortality and yellow cedar decline are often coincident, because warmer winter sites favor aphid survival, but provide less snow to protect yellow cedar roots. A warm spring, coupled with a late freeze, can increase mortality of both yellow cedar and spruce aphids. Higher winter temperatures will facilitate movement of Sitka aphids toward the mainland and expand the area and frequency of attack.

Mountain pine beetle (*Dendronus ponderosae* Hopkins) attack lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.). Recently, the beetle has moved north into Canada devastating lodgepole pine forests and now has reached the Yukon Territory. Lodgepole

pinus in Haines and Skagway may soon be infected, and the closely related shore pine (*Pinus contorta* Dougl. var. *contorta*), common in the bogs of southeastern Alaska, could be impacted if the pine beetles switch hosts. Mountain pine beetles have moved up in elevation at nearly twice the rate of their host forests and are expected to shift to even higher latitudes and elevations (Williams and Liebhold 2002).

White pine weevils currently infest trees in British Columbia, not far from susceptible young growth trees in Alaska. In the leaders of Sitka spruce, the weevils can survive down to 14°F (Hulme *et al.*, 1986), a low temperature rarely recorded in the lower elevations of southeastern Alaska where Sitka spruce are common.

### Fish

Pacific salmon are economically and socially important in southeastern Alaska, and more salmon are caught in Alaska than anywhere else along the west coast of North America (Howe *et al.* 2001; Clark *et al.* 2006). Furthermore, in contrast to many salmon fisheries along the west coast of the United States, most salmon fisheries in southeastern Alaska maintain sustainable escapements (Baker *et al.* 1996). The large number of salmon stocks adapted to local conditions represents an immense genetic reservoir (Halupka *et al.* 2003). Climate plays an important role in the development of specific stock characteristics, and rapid climate change can significantly affect anadromous salmonid populations. Temperature and rainfall control several critical stages in the life cycle of salmonids. Locally, sea level is projected to decrease with climate warming affecting salmon populations that reside in low elevation freshwater habitats.

Five Pacific salmon species, pink (*Oncorhynchus gorbuscha*), chum (*O. keta*), coho (*O. kisutch*), sockeye (*O. nerka*), and chinook (*O. tshawytscha*), reside in southeastern Alaska (Mecklenburg *et al.* 2002). Each species will be affected by climate change according to its specific life history. Pink and chum salmon often spawn in the lower reaches of rivers, although some chum salmon may migrate considerable distances upstream. Chum and pink salmon fry (fish in their first summer) emerge from the gravel from April through May and migrate to the ocean in a few weeks. Sockeye, Chinook, and coho salmon

spawn in freshwater and the fry generally spend one or more years in freshwater. Some sub-groups of Chinook and sockeye stocks, however, migrate to the ocean shortly after emergence.

*Pink and chum salmon*-- Increasing temperatures will likely alter spawning success and fry survival. Spawning pink and chum salmon enter freshwater in large numbers over several weeks during the late summer when stream temperatures are often close to the maximum for the season. They often hold in deep pools during periods of low flows. The combination of high temperature, low flows, and high fish density rapidly depletes dissolved oxygen in the water resulting in high pre-spawning mortality (Murphy 1985; Pentec 1991). In the past, episodes of large pre-spawning mortality were infrequent and mostly confined to the southern portion of southeastern Alaska. As temperatures increase, these events are likely to become more common and occur in more northern watersheds of southeastern Alaska.

Changes in temperature, especially during the early part of incubation, can affect time of emergence of pink and chum salmon (Heard 1991 and Salo 1991). Fry of both species migrate to the ocean when food is abundant in inter-tidal areas. Increasing temperatures will hasten emergence and the onset of migration in both species. Early entry into the marine environment, when food resources are low or absent, will decrease growth and survival. The consequences for pink and chum salmon populations in Juneau are complicated by the existence of the DIPAC hatchery. The ability to artificially control hatchery temperature could mitigate some local impacts of a warmer climate.

*Sockeye salmon*-- Small populations of sockeye salmon are present in two lakes on the Juneau road system, Auke and Windfall lakes. A larger population passes through the Juneau area to spawning locations in the upper watershed of the Taku River. They enter freshwater during the summer and reside in the lakes before migrating into tributaries to spawn. Some may spawn along lake margins. Changes in temperature regimes may shift spawning timing and time of emergence of sockeye fry with unknown effects on growth

and survival. Lakes are susceptible to warming which can increase stress on adult sockeye holding in lakes.

Temperature increases are likely to affect growth and survival of sockeye fry that rear in lakes for one to two summers. Mean summer temperatures in lakes throughout Alaska seldom rise above 57°F and are below 50°F most of the time. Higher temperature may increase growth rates and, thereby, food requirements. Climate change may also affect the trophic structure of lakes (Magnuson *et al.* 1990). The duration of summer stratification increased and vernal mixing occurred earlier with increasing temperature (Winder and Schindler 2004). As temperatures increase, phytoplankton and zooplankton populations peak earlier in spring before the peak needs of feeding salmon. The earlier timing of zooplankton blooms may not translate in to greater amounts of zooplankton (MacDonald *et al.* 1996; Winder and Schindler 2004).

Predation can have a substantial effect on juvenile sockeye salmon in lakes (Cartwright *et al.* 1986). Alterations in the trophic status of lakes may also change dynamics of other species. The effect of higher temperatures in Alaskan lakes on cutthroat trout is not known; however, higher temperatures may increase metabolic requirements for cutthroat trout and increase predation rates on juvenile sockeye salmon.

*Chinook Salmon*-- A small population of Chinook salmon resides in King Salmon Creek on Admiralty Island, and commercially important numbers migrate to drainages in the upper Taku River watershed. That interior region will likely experience greater warming and drying than will coastal habitats. The higher temperatures may promote earlier emergence negatively affecting feeding, growth, and survival. Thermal refuges and deep cold pools are commonly used by adult chinook migrating up large rivers, and increased temperatures will increase metabolic costs during migration (Berman and Quinn 1991). Effects in the Taku River are likely to be complicated by increased glacial melting. Initially, increased glacial melting may decrease downstream temperatures as well as increase the magnitude of seasonal floods. Both effects are likely to decrease the quality

of habitat for juvenile Chinook salmon and other species such as coho salmon rearing in freshwater habitats in the lower reaches of the river (Berggren and Filardo 1993).

*Coho Salmon*-- In southeastern Alaska, juvenile coho salmon typically spend two summers in freshwater. In most streams, mean daily temperatures usually do not exceed 40°F until late May and by mid September are below 43°F. Increased temperatures may increase growth rates and decrease residence time in freshwater from two summers to one summer. Larger smolt tend to have higher ocean survival rates than smaller smolt, hence, ocean survival may decline with increasing stream temperature. That decline may be offset, however, by lower freshwater mortality.

A substantial, but largely undocumented, number of juvenile coho salmon use off-channel habitats such as beaver ponds and sloughs (Bryant 1984a; Swales and Levings 1989; Pollock *et al.* 2004; Schaberg 2006). Temperatures in some of these ponds may be 4 to 7°F warmer than the adjacent free flowing stream (Bryant unpublished data) and are close to physiological optima for growth during the summer. Higher temperatures in these habitats are likely to exceed physiological limits for growth and, in some cases, reach lethal limits.

Growth and survival of juvenile coho salmon are highly dependent on seasonal flow rates in streams. One consequence of a warmer climate will be lower summer flows and higher winter flows. Low flows that reduce the size and depth of pools accompanied by increases in temperature will impose higher mortality and reduced growth rates among coho fry. Furthermore, invertebrate drift (an important food source) will also decrease with lower flows (Hetrick *et al.* 1998). In contrast, more frequent and intense episodes of heavy rain and high intensity flood events during the fall and winter will increase landslides and mass wasting, removing wood and diminishing pools that are important over-winter habitats (Tripp and Poulin 1986; Johnson *et al.* 2000).

Many habitats used by juvenile coho salmon in the lower Taku River would likely be inundated with a modest (3 ft) increase in sea level (Murphy *et al.* 1989). Rising sea

levels will flood low elevation habitats converting freshwater habitats into brackish or saline environments. Habitats above the immediate effects of flooding will become intertidal and subject to periodic tidal flooding and pulses of saline water and will no longer provide viable freshwater habitat for juvenile coho salmon.

*Management consequences*—All five species of Pacific salmon found in southeastern Alaska are present in lower latitudes where ambient temperature are considerably warmer than those found in southeastern Alaska. Wholesale extirpation of salmon stocks in the southeastern Alaska as a direct result of global climate change is unlikely. The stocks in southeastern Alaska, however, have evolved strategies suited for the present climate regime. Their persistence in the face of a changing environment will depend in part upon their ability to adjust to these changes. Genetic diversity and rates of climate change will be significant influences on adaptation. Regardless of adaptation, increased natural mortality and higher year-to-year variation in numbers may be expected as stocks respond to new conditions. Rapid changes (i.e. those occurring over a period of decades) are likely to impose increased stress on stocks that have adapted over centuries to specific environments. A common concern in several assessments of the effect of climate change on aquatic ecosystems is the interaction with existing effects of other anthropogenic disturbances having a cumulative effect on reproduction (Hauer *et al.* 1997). Among these disturbances are chemical and thermal pollution, dams, habitat deterioration, and introduced species. Furthermore, these disturbances tend to be localized near urban areas such as Juneau.

The severity of the effects will be related to the rate of change in water temperatures and precipitation. Assuming an annual temperature increase of 0.2°F, detecting statistically significant shifts in mortality, migration timing, or other potential responses will be difficult over a period of less than 10 years. Year-to-year variations in run sizes are likely to be large and the result of many complex variables from ocean temperatures to winter snow pack in mountains. Given that rapidly changing climate will impose additional stress on populations, more conservative management may be appropriate. It may be

necessary to manage streams to preserve thermal refugia, critical habitats, and intact watersheds and to manage harvests conservatively.

### Amphibians and Reptiles

Eight species of amphibians (2 salamanders, 1 newt, 5 frogs) - but no reptiles - exist in southeastern Alaska (McDonald 2003): roughskin newt (*Taricha granulosa*), long-toed salamander (*Ambystoma macrodactylum*), northwestern salamander (*Ambystoma gracile*), western toad (*Bufo boreas*), Columbia spotted frog (*Rana pretiosa*), wood frog (*Rana sylvatica*), red-legged frog (*Rana aurora*), and Pacific chorus frog (*Pseudacris regilla*). The red-legged frog and pacific chorus frog are introduced species. Little is known about these species in southeastern Alaska other than their general distribution and habitat use (McDonald 2003). The affect of changing climate on amphibians living in southeastern Alaska is unknown. Moisture availability is very important to amphibians, however, and warming temperatures affect the rate of pond desiccation (Inkley *et al.* 2004).

The Alaskan toad and frogs belong to the taxonomic families that are declining more rapidly world-wide than the average for other amphibians (Stuart *et al.* 2004). Declines are attributed to capture and removal, reduction in habitat, or “enigmatic” reasons. Disease and changes in climate, particularly moisture conditions, are other commonly cited explanations for declines (Stuart *et al.* 2004). Disease or climate change may be important factors affecting the future trends for these species in southeastern Alaska. The fungal disease chytridiomycosis is more frequent among species living at higher elevations and along steam-side (Stuart *et al.* 2004). Stuart *et al.* (2004) expect “hundreds of species of amphibian...to become extinct over the next few decades.”

Amphibian skin is permeable making them vulnerable to cell-damaging changes in ultraviolet radiation (Cockell and Blaustein 2001, in Inkley *et al.* 2004) and pollutants in the air. Ozone depletion, via chlorofluorocarbon emissions, has allowed elevated levels of ultraviolet radiation to occur world-wide. Air pollutants emitted locally or carried to southeastern Alaska from around the globe may be contributing to local declines.

As the climate has warmed, the altitude of cloud banks in the Costa Rican rain forest has increased with a concomitant decrease in mist within the forest (Pounds *et al.* 1999). Something similar may be happening in southeastern Alaska rain forests. Frogs may show warming affects first on low elevation, south facing slopes where temperatures will be higher and conditions drier.

### Birds

Over 150 species of birds occurred in southeastern Alaska in the early 1980s (Gibson 1984). More recently, 184 species were observed (Johnson *et al.* in press). Some warblers responded to increasing temperatures by shifting their breeding ranges significantly north (Inkley *et al.* 2004). Birds, because they are capable of flight, can expand their range more readily than other animals or plants. It is uncertain how climate change will affect each species in the long-term. Unlike year-round resident birds, migratory breeders are challenged to match the time of nesting with availability of food. Typically, migratory species time their arrival on breeding grounds with the peak production of food. As the climate has warmed, the arrival of spring has advanced. Some bird populations cannot track the swiftly changing climate and may decline, others may be able to keep pace with the changes. For example, in Arizona, the Mexican jay has nested increasingly earlier over 27 years as the average daily minimal temperature climbed almost 0.2 °F each year. The jays benefited from earlier activity of their insect food and decreased energy needed to stay warm during the night.

Other species may “be caught in a race against time” (Thomas *et al.* 2001). Unlike the Mexican jay, which is able to track the changing climate, the breeding cycle of blue tits (*Parus caeruleus*) in the Mediterranean is increasingly out of synchrony with food availability resulting in greater mortality rates. A similar observation has been made for great tits (*Parus major*) in Europe (Visser *et al.* 1998 in Inkley *et al.* 2004). Dutch populations of the migratory pied flycatcher (*Ficedula hypoleuca*) have declined by 90% over two decades in which their insect prey have peaked increasingly early and before the birds arrived at the breeding sites (Both *et al.* 2006). The flycatchers were able to

advance their egg laying dates once they arrived at northern breeding areas, but they were unable to advance their arrival time, and their breeding became progressively distant in time with the peak production of their prey. A species' ability to adjust may not be quick enough to match rapid climate changes and, it may become locally extinct. The rate of climate change for interior Alaska is expected to be so swift, that migratory birds may not be able to adjust.

Resident birds of the Sitka spruce and western hemlock forest in southeastern Alaska, such as blue grouse, may benefit as that forest type moves upslope and expands in size as warming trends continue over this century. Alpine habitat, for species such as ptarmigan, is predicted to be reduced, fragmented, or even eliminated as it is converted to spruce/hemlock forest. In contrast to interior Alaska, southeastern Alaska's maritime weather is expected to moderate the speed at which warming occurs.

As particular species increase or decline in response to the warming climate, the species with which they interact also will be affected. For example, warmer temperatures favored a massive increase of spruce beetles. The beetles killed white spruce trees in the Copper River area. The large tree die-off decreased the density of ruby-crowned kinglets (*Regulus calendula*) as their habitat structure changed. The extensive tree mortality, however, opened the forest allowing shrubs to proliferate and concurrently greatly reduced the population of an important avian nest predator (red squirrel) (Matsuoka *et al.* 2001). The opening of the forests and the reduction of nest predators overall appears to have benefited breeding birds (Matsuoka *et al.* 2001).

### Mammals

Fifty-four terrestrial mammals have been documented in southeastern Alaska (MacDonald and Cook 1999). The fate of small mammals living above the spruce/hemlock forest may be similar to species living on mountaintops in the Great Basin desert of North America where they are currently restricted to habitat islands at the higher elevations. They are prone to extinctions as their habitats shrink until they are "pushed off the top of the mountain" (Brown 1993).

The Mt. Graham red squirrel (*Tamiasciurus hudsonicus grahamensis*), with less than 300 individuals remaining, is an example of a mammal isolated on a southern Arizona forest mountaintop surrounded by desert (Koprowski *et al.* 2005). As the climate continues to warm, the size of area containing conifer tree habitat will continue to shrink. This effect is compounded by the effect warming has on insect activity. Insects that thrive in warmer temperatures are increasing and devastating plants on which some mammals depend. Mt. Graham Red squirrels are declining as their conifer tree seed source is being killed or defoliated by geometrid moths (*Nepytia janetae*), spruce beetles (*Dendroctonus rufipennis*), western balsam bark beetles (*Dryocoetes confusus*), and spruce aphids (*Elatobium abietinum*) (Koprowski *et al.* 2005).

As the climate continues to change, shifts in advantage among species may occur. The muskrat (*Myocastor coypus*) feeds on sedges, which benefit (due to their use of C<sub>3</sub> photosynthetic pathway) as warming continues, while competitors feeding on grasses (C<sub>4</sub> photosynthetic pathway) will be at a disadvantage (Inkley *et al.* 2004). The consequences of warming and competition and its effect on distributional patterns, extent of range overlap, and interspecific competition between the northern flying squirrel (*Glaucomys sabrinus*) and southern flying squirrel (*G. volans*) in the eastern United States may be illustrative of potential affects on mammals in southeastern Alaska (Smith 2007).

Continued warming may also interact with land use practices that reduce forest canopy cover to decrease the amount of suitable habitat for forest specialists like the endemic Wrangell Island red-backed vole (*Clethrionomys gapperi wrangeli*). Red-backed voles have high water requirements and are ordinarily excluded from clearcuts and young second-growth stands of western coniferous forest, because conditions are too dry in the exposed ground vegetation (Smith and Nichols 2004). Unlike the Pacific Northwest, young managed rainforests of southeastern Alaska provide marginal habitat for red-backed voles (Smith and Nichols 2004), but continued warming could increase fragmentation of red-backed vole populations by rendering clearcuts and young second-growth stands unsuitable. The extent to which other mesic forest specialist will be impacted remains unclear, but continued warming and drying will likely reduce the

abundance and diversity of fungal communities (Meyer and North 2005), a potentially important food item of several endemic small mammals, including flying squirrels (Smith 2007).

Isolation associated with the dynamic geologic history of southeastern Alaska resulted in a fauna that includes 27 endemic species (MacDonald and Cook 1996; Smith 2005). Naturally fragmented habitat on oceanic islands has long been recognized as a population limiting constraint that maintains the size of island populations below those of mainland populations (MacArthur and Wilson 1967). Rapid climate change will likely have significant negative effects to endemic species living in southeastern Alaska in part due to their isolation on islands.

Thousands of species exist in southeastern Alaska ecosystems. The ability of each species to adjust to swift climatic change is different and their success hinges in part on their physiological flexibility, reproductive capability, and ability to compete with and maintain their interdependence on other species that must also simultaneously adapt to survive. The resilience of species in southeastern Alaska ecosystems to adapt to quick change remains unknown. Predicting the ecological impacts of warming climate is complicated by other concurrent anthropomorphic disturbances that are occurring simultaneously.

### **Marine ecosystem**

The impacts of climate change on fish harvests can be postulated for Juneau and Southeastern Alaska from observed changes in other areas the North Pacific Ocean and the world. Warming temperatures in the Gulf of Alaska may enhance plankton populations and lead to increases in salmon, pollock, and other commercially important fish species (McGowan *et al.* 1998). Elsewhere, however, warming temperatures have that opposite effects, and the response of the marine ecosystem is difficult to predict (Walther *et al.* 2002; McGowan *et al.* 1998).

Shorelines and wetlands are integral nursery areas for many marine species and will be threatened by increasing intensity and frequency of coastal storms. Near shore fish habitats will be altered by changes in precipitation patterns and subsequent delivery of freshwater, nutrients, and sediment; increased ocean temperature; alterations in circulation patterns; changes in frequency and intensity of coastal storms; and increased levels of atmospheric CO<sub>2</sub> (Scavia et. al. 2002).

Throughout the North Pacific, warming ocean temperatures are expected to cause shifts in the ranges of many organisms toward the poles (Walther *et al.* 2002). These shifts may have secondary effects on predators and prey of affected species potentially leading to large scale changes in the composition of the marine community.

Juneau and southeastern Alaska area fisheries are influenced by proximity to the Gulf of Alaska. Climate induced changes in near shore flows and eddies of the Gulf affect much of the region's biological variability, and the distribution of fish likely will change as flow patterns change. Dramatic changes in the species composition of the near shore demersal fish community in the Gulf of Alaska in the late 1970s and early 1980s were related to such oceanographic changes. The species composition and spatial distribution was more stable from 1984 through 1996, a period with less pronounced variations in the physical environment, although non-commercial species such as skates and capelin continued to be quite variable (Mueter and Norcross 2002). Capelin abundance increased, possibly in response to increasing abundance of large predatory fishes. Phytoplankton and zooplankton biomasses declined in the Gulf of Alaska with a climate shift in 1976 associated with the Pacific Decadal Oscillation (Aita et. al. 2006). In the subsequent year, the seasonal peak in plankton biomass was earlier than in previous years (Alexander *et al.* 2006). Such changes in the timing of the spring bloom affect survival, especially of juvenile fish (Beamish et. al. 2006).

Within the Bering Sea, the southeastern shelf has warmed, a trend that may alter the abundance and distribution of commercially fished species (including pollock, cod, salmon, and shellfish), hinder the recovery of Steller sea lions and northern fur seals, and

decrease resources available to subsistence users (Bering Sea Interagency Working Group 2006).

The sensitivity of the marine environment to temperature changes was demonstrated by an abrupt change from cold to warm water in the Japan/East Sea in the late-1980s (Tian *et al.* 2006). Subsequent changes in plankton communities led to large changes in the composition of Japanese fish catches. Sardine catches decreased abruptly, while anchovy, squid, yellowtail, and tunas catches increased.

In addition to the effects on global temperatures, increases in CO<sub>2</sub> emissions are increasing the acidity of the oceans. As ocean acidity increases, the skeletal growth of calcium-secreting organisms is reduced. If acidity becomes too high, shells will dissolve faster than they can be built (Orr *et al.* 2005). The loss of shelled organisms would have pronounced negative effects on many other members of the marine food web including salmon, herring, and cod.

As climate change and human populations put increasing pressure on fishery resources, the technical, regulatory, and economic processes used to conserve and sustain species and their habitats will face greater uncertainty. Fishery managers in the North Pacific have embraced ecosystem management, and NOAA scientists have developed ecosystem models for species targeted by commercial fisheries where sufficient life history and food habits data are available (Boldt 2006). These models are being used to explore scenarios of increasing and decreasing abundance of target species and their predators and prey. The models may help predict ecosystem responses to climate changes.

### **Socioeconomic responses**

Alaska is responding to warming by creating forums to discuss climate change and engaging the scientific community to begin managing change. While some opportunities - increased agriculture resulting from a longer growing season, for example - may result (Chapin 2006), the state faces myriad challenges including decreased winter tourism, more wildfires, less stable permafrost, altered salmon runs, more invasive species, and storm erosion along northern coasts. These events will require Alaskans to adapt and become more resilient. To cope with changes associated with warming, Alaska will need to create innovative and adaptive management and co-management strategies locally and regionally.

Socioeconomic impacts of climate change on Juneau are evident in the published literature, government reports, and interviews with economists and experts in climate research. Also informative is the approach of other communities to addressing the socioeconomic impacts of climate change. Juneau both contributes to and is affected by climate change, and many consider it our obligation to assess our contributions to climate change (ICLEI 2007). Hundreds of communities have recognized and are addressing their emissions of greenhouse gases and the impacts on climate change.

Assessments of socioeconomic impacts of climate change have recently begun to appear (IPCC 2001). The effects have been assessed for only a few economic sectors, such as agriculture and timber, at the global scale. Some research at the national level has used

large scale ecological data linked to economic models to predict gross domestic products and population growth (McKibbin, and Wilcoxon, 2002). These studies, however, did not incorporate several non-market sectors which must to be considered if social impacts are to be considered (Larsen 2006). Such non-market sectors might include cumulative effects on local ecological systems such as forested wetlands in Juneau.

Studies on climate warming and socioeconomic impacts at the regional and local level are still rare (Cohen 2006). An Alaskan economist recently pointed to three main difficulties in assessing the impact of climate change on local socioeconomics (Larsen 2006).

- (1) Challenges in “downscaling” the general circulation models’ (GCMs) results,
- (2) Correlating economic activity to weather/climate, and
- (3) Economic production and the disconnect with societal wellness.

Local climate change is influenced greatly by local features such as mountains, which are not well represented in the coarse resolution of global models. Models of higher resolution cannot practically be used for global simulation of long periods of time. To overcome this, regional climate models, with a higher resolution (typically 50 km) are constructed for limited areas and run for shorter periods (20 years or so).

Researchers at the Institute of Social and Economic Research (ISER) in Anchorage currently are developing a regional climate model for use in socioeconomic analyses (Larsen 2006). The model will allow predictions at a regional and possibly local level.

Traditional economic models applied to other parts of the United States lack the strong subsistence components that are important in Alaska’s economy. Economic models, that include the impacts of climate change on subsistence users (Cohen 2006), need to be developed for Juneau and southeastern Alaska.

The rapid rate of warming in high latitudes has already had substantial impacts on local communities. Several villages in northwestern Alaska are being threatened by coastal erosion, patterns of travel are being altered by changes in snow and ice cover, subsistence hunting is being disrupted by habitat changes, and infrastructure is threatened by melting permafrost and increased coastal erosion (Chapin and Walsh 2005; Larson 2006; National Oceanic and Atmospheric Administration 2007). Juneau's climate also is warming more rapidly than that of lower latitudes, and climate change impacts to Arctic and Sub-Arctic communities may be relevant to Juneau's case.

ISER is estimating the value of Alaska's public infrastructure at risk from climate change (Larsen 2006). They suggest the following possible impacts, some of which may apply to Juneau.

- Difficulty maintaining subsistence hunting cultures
- Expanded marine shipping
- Declining food security
- Human Health concerns (increased incidence of vector-borne diseases and asthma)
- Effects on wildlife migratory patterns
- Improved access to offshore resources, including minerals and petroleum
- Changes in marine fisheries
- Decline in freshwater fisheries such as arctic char and salmon
- Enhanced agriculture growing seasons
- More forest fires and increased insect infestation
- Disrupted land transportation from thawing permafrost and melting ice roads
- Increased damage to community infrastructure from coastal erosion and melting permafrost

Some of the severe impacts experienced in northern Alaska (increased flooding, sea level rise, and excessive erosion associated with decreased sea ice cover) are not threats to Juneau. Juneau, however, will be challenged by abrupt changes to natural communities and, thereby, to commercial and subsistence harvests of fish and wildlife; reduced snow

cover and associated winter recreation, increased rainfall and flooding; and changing patterns of fossil fuel consumption. The latter potentially will negatively impact transportation to Juneau for residents and tourists.

Potential socioeconomic impacts on Juneau's economy, human health, and public infrastructure are summarized below.

#### Economic

Increased precipitation may strain public and private infrastructure such as water and wastewater discharge systems. Impacts of higher temperatures on local mining are likely to be minimal, although increased precipitation may increase erosion and sedimentation.

Transportation to and from – and to a lesser extent within – Juneau involves consumption of large but unknown amounts of fossil fuels. Much of that transportation is associated with Juneau's strongest growth industry, tourism. From 1995 to 2005, the number of passengers on cruise ships in Juneau grew from 250,000 to 800,000 (CBJ 2006). Nationwide, the transportation industry is the largest contributor to CO<sub>2</sub> emissions, accounting for 1/3 of all emissions (Greene and Schafer 2003). World-wide, cargo and passenger vessels consume the majority of the marine bunker fuel sold (Endresen *et al.* 2003). The airline industry accounted for 13% of transportation-related CO<sub>2</sub> emissions in 1992, but rapid growth in that industry may increase its emission by more than a factor of ten by 2050 (Penner *et al.* 1999). Regulatory and/or market pressures to reduce transportation related emissions of greenhouse gases potentially will impact Juneau's tourism industry, currently the source of approximately 2,000 jobs in the community. Coincident with such changes will be increased costs for all modes of carbon-dependent transportation with impacts to the distribution of food and goods to the CBJ.

Much of the winter recreation in Juneau depends on snow cover. Continued warming will decrease that snow cover prompting a proposal to build a chairlift at a higher elevation on Juneau's Eaglecrest ski area. Skiing, sledding, ice skating and other snow-dependent activities will be less available to Juneau residents as the climate warms. If people leave

Juneau to find winter recreation elsewhere, money will be lost from the local economy. To the extent that people divert their “winter recreation” funds into other sectors of the economy (restaurants, movies, or other entertainments) the impact on the overall economy will be ameliorated.

Seasonal timing and yields of commercial, subsistence, and recreational fisheries likely will decline as a result of ecological changes associated with climate change. Opinion surveys and participation records consistently indicate that recreation and the use of recreation facilities are important values to Juneau residents (City and Borough of Juneau 1996; Sharmon *et al.* 1999).

#### Human Health Effects

As with other organisms, the distributions of disease agents are changing as temperatures increase, and in some instances their virulence and the duration of the transmission season also will increase (Epstein *et al.* 1998). Mosquito carriers of encephalitides, for example, are likely moving northward in the continental United States and in Canada (Reisen *et al.* 1993; Reeves *et al.* 1994).

*Echinococcus multilocularis*, a parasitic worm known to be fatal in human beings (Rausch 1967; Fay 1973), recently expanded its range along with its host to the North Slope of Alaska (Bradley *et al.* 2005). The H5N1 strain of avian influenza infects many birds in Southeast Asia and may well have arrived with migratory birds in Alaska (Bradley *et al.* 2005). The mortality rate for people infected with avian influenza is over 50%.

Rising air temperatures are predicted to increase asthma (IPCC 2001). In southeastern Alaska, warming temperatures and die-offs of trees (e.g. yellow cedar) are expected to increase the frequency of forest fires and, thereby, increase respiratory difficulties for people in the region.

Increased storm frequency and intensity may also increase injuries and deaths, especially in the boating community.

### **Suggested CBJ responses**

Continued global warming will be socially and economically costly. Increasing the energy efficiency of private and public buildings and transportation systems will provide immediate economic benefits as well as reduce the long-term costs associated with large-scale environmental changes.

Municipal and state governments increasingly are responding to changing climate, and many are finding support in the U. S. Conference of Mayors' *Climate Change Protection Agreement* and the International Council for Environmental and Local Initiatives' (ICELI) *Climate Change Program*). At least 650 communities worldwide, including 138 communities in the United States, have agreed to establish a Climate Change Program (U. S. Conference of Mayors 2005; ICLEI 2007). These communities have committed to participate in the "Cities for Climate Protection Program" (CCP) established by the ICELI. The communities commit to conducting a five step process consisting of:

- 1) conducting a baseline inventory and emissions forecast
- 2) adopting an emission reduction goal
- 3) developing a local action plan
- 4) implementing emissions reduction measures and policies
- 5) monitoring and verifying results.

As of March 2007, over 430 Mayors representing 6,000,000 Americans have signed on to the U. S. Mayors' *Climate Protection Agreement* (US Conference 2005) Climate Protection Agreement. The agreement urges the federal government to enact policies and programs to reduce global warming pollution levels to 7% below 1990 levels by 2012 (US Mayors 2007). The agreement lists twelve specific actions including recycling, energy saving measures, changing land-use policies, and increasing use of alternative fuels.

Some government practices slowing climate change include: establishing electronic offices (E-government), improving mass transit, expanding recycling, and increasing the energy efficiency of buildings by using LED lights and updated heating and cooling systems.

## **Appendix – Values of fisheries in southeastern Alaska**

### **Subsistence fisheries**

Within the state, the composition of subsistence harvests is 65% fish, 18.5% game, 9.7% marine mammals and 6.4% other. Wild food harvests in Juneau were surveyed in 1992 and estimated at 34.5 pounds per person annually and 0.095 pounds per person daily.

These harvest data indicated that Juneau residents derived approximately 22% percent of recommended dietary allowance of protein (49 g of protein per day, or 0.424 lbs of wild food per day) from wild foods (Alaska Department of Fish and Game 2006a).

The CBJ is considered a nonsubsistence area defined as “an area or community where dependence upon subsistence is not a principal characteristic of the economy, culture, and way of life of the area or community (AS 16.05.258© and 5 AAC 99.015). Subsistence fishing activities can be considered localized because of the culture and economy of users and the micro-ecology within a geographic area. Residents of CBJ commonly fish, but the activity is more typically characterized as a part of non-economic (recreational) pattern, both locally and in surrounding rural areas (Wolfe 2004). Subsistence harvesting is open to Native and non-Native Alaskans, although the non-natives are prohibited from hunting protected species. Subsistence fishing activity in Juneau can be measured two ways. One measure is the number of household permits to catch personal use/subsistence salmon and crab. In census year 2000, 602 household permits were issued and returned with reported harvest of 4,458 salmon. In 2005, 543 permits reported 5,717 salmon harvested (David Harris, Alaska Department of Fish and Game, personal communication). The second measure is certificates for halibut fishing. In 2003, regulations to implement subsistence halibut fishing were implemented issuing rural and Alaska Natives federal Subsistence Halibut Registration Certificates (Sepez, et. al. 2005). Two tribal entities associated with Juneau were identified as receiving certificates in

2006: Central Council of Tlingit and Haida Indian Tribes and Douglas Indian Association, receiving 725 and 25 certificates, respectively (National Oceanic and Atmospheric Administration 2006).

### Commercial fisheries

The Juneau, Douglas, and Auke Bay communities have commercial fisheries landings, are registered as home ports of vessels participating in commercial fisheries, and are home to documented participants in the permitted commercial fisheries for Dungeness crab, red/blue/golden king crab, Tanner crab, halibut, herring, lingcod, miscellaneous finfish, rockfish, sablefish, salmon, sea cucumber, and shrimp. In census year 2000, Juneau City and Borough was the documented residence of 520 commercial vessel owners and 521 commercial fishing permits holders with 959 permits for all fisheries of which 518 were fished. In 2005, numbers declined to 344 vessels, 455 permit holders that held 868 permits of which 395 were fished. In 2000, a total of 17,500,000 pounds of fish were landed on resident permits while in 2005 the amount increased to 21,700,000 pounds of fish. Estimated gross earnings were \$14,800,000 in 2000 and \$11,800,000 in 2005 (State of Alaska 2006). Commercial landings of 7,600,000 round pounds were made to 28 processors in 2000 with an ex-vessel value of \$15,000,000. In 2004, 12,800,000 round pounds worth \$20,800,000 were landed at 53 processors (Cathy Tide, Commercial Fisheries Entry Commission, personal communication).

### Recreational fisheries

The area's freshwater streams, lakes, hatcheries, and saltwater shorelines, adjacent bays, inlets, and canals support productive sport fisheries for all five species of salmon, Dolly Varden, cutthroat trout, halibut, rockfish, Lingcod, shrimp and crab. Juneau area sport fish effort and harvest provide an index of recreational fishing activity by residents and non-residents. In 2000, 27,252 anglers made 83,005 trips logging 128,481 days fished and 109,603 fish landed. Recreational fishing appears stable with most recent available data for 2004 documenting 29,452 anglers made 79,127 trips for 125,803 days fished yielding 113,027 fish (Alaska Department of Fish and Game 2006b).

Sport fishing is most common during milder weather months of spring and summer when salmon return for spawning. Recreational fishing in Juneau is engaged in privately and by using guiding and charter service. Alaskans and visitors value and benefit from recreational fishing. Economic value is a measure of the value anglers place on sport fishing including tangible, what they actually pay for the experience, and the intangible benefit people get from the activity such as pleasure of spending time in a scenic area. Recreational fishing contributes to the Juneau economy through jobs, income, and sales of fuel, fishing gear, bait, food, lodging, transportation, and services such as repair and charter (Sharman et. al. 1999).

Climate change has potential to impact recreational fishing in two ways: indirectly through physical resource changes in biodiversity and water levels on which nature-based recreation depends and directly in terms of length and quality of season; participation and demand; and experience satisfaction. Canadian studies project loss of recreationally valued freshwater fish populations, especially cold- and cool-water fish species as lakes and rivers warm causing temperature-induced habitat loss and range shifts. This warming is attributed to later winter freeze up, reduced duration of ice cover, and earlier spring break up on lakes and rivers. Increased rainfall may cause unseasonable flooding in river drainages, impacting spawning habitat and damaging recreational access and facilities (Scott and Jones 2006).

A study of national park visitation in Canada under warming climate scenarios found that increased visitation could be expected during spring (April to June) and fall (September to November) as climate conditions become more suitable for outdoor recreation. Changes in seasonal timing of increases in visitation will influence a range of management and operation decisions for government and private industry (Scott and Jones 2006).

#### Aquatic farming

Mariculture of shellfish and aquatic plants occurs in southeastern Alaska, but only two aquatic farm permit holders reside in Juneau. One intertidal geoduck farm is located

within the City and Borough of Juneau but not yet in production (Cynthia Pringham, Alaska Department of Fish and Game, personal communication). There are no finfish farms as Alaska statute prohibits finfish farming (AS 16.40.210) (Timothy and Petree, 2004). Three fish hatcheries producing five species of Pacific salmon operate within the vicinity of Juneau (McDowell Group 2001).

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