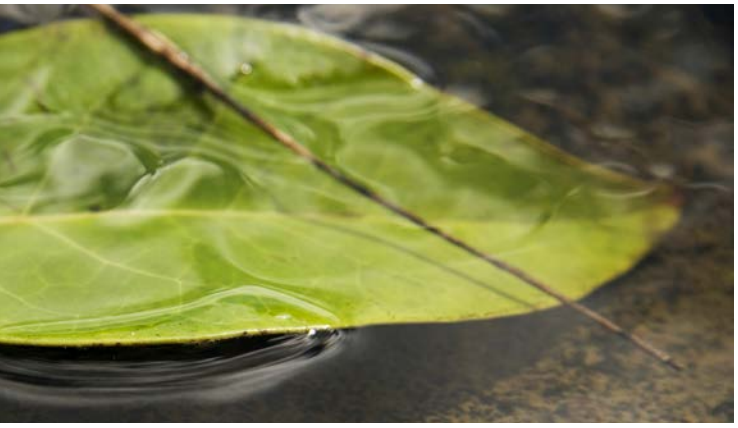

Recent US Climate Change and Hydrology Literature Applicable to US Army Corps of Engineers Missions

ALASKA REGION 19

FINAL

September 2015

USACE CLIMATE PREPAREDNESS AND RESILIENCE

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14. ABSTRACT
To help the US Army Corps of Engineers (USACE) staff in meeting the requirements of the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance, this report presents concise and broadly-accessible summaries of the current climate change science with specific attention to USACE missions and operations. This report, focused on the Alaska Region, is part of a series of twenty one (21) regional climate syntheses prepared by the USACE under the leadership of the Response to Climate Change Program at the scale of 2-digit Hydrologic Unit Code (HUC) Water Resources Regions, across the continental United States, Alaska, Hawaii, and Puerto Rico. Each of these regional reports summarize observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterize climate threats to USACE business lines.

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ALASKA REGION 19

September 11, 2015

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Water Resources Region 19: Alaska Region

1. Introduction

U.S. Army Corps of Engineers (USACE) staff are increasingly considering potential climate change impacts when undertaking long-term planning, setting priorities, and making decisions that affect resources, programs, policies, and operations, consistent with the 2011 and 2014 policy statements on climate change adaptation by the Assistant Secretary of the Army for Civil Works, the USACE Climate Change Adaptation Plans, and agency policy and guidance. USACE is undertaking its climate change preparedness and resilience planning and implementation in consultation with internal and external experts using the best available – and actionable – climate science and climate change information. This report represents one component of actionable science, in the form of concise and broadly-accessible summaries of the current science with specific attention to USACE missions and operations. This report is part of a series of twenty-one regional climate syntheses prepared by the USACE under the leadership of the *Response to Climate Change Program* at the scale of the 2-digit U.S. Geological Survey (USGS) Hydrologic Unit Codes (HUC) across the continental United States, Alaska, Hawaii, and Puerto Rico. The twenty-one Water Resources Regions included in this series of reports is shown in **Figure 1.1** along with USACE division boundaries. Each of these regional reports summarizes observed and projected climate and hydrological patterns cited in reputable peer-reviewed literature and authoritative national and regional reports, and characterizes climate threats to USACE business lines. They also provide context and linkage to other agency resources for climate resilience planning, such as sea level change calculation and coastal risk reduction resources, downscaled climate data for subregions, and watershed vulnerability assessment tools.

This report focuses on Water Resources Region 19, the Alaska Region, the boundaries for which are shown in **Figure 1.2**. The region is fully within the Alaska USACE district.

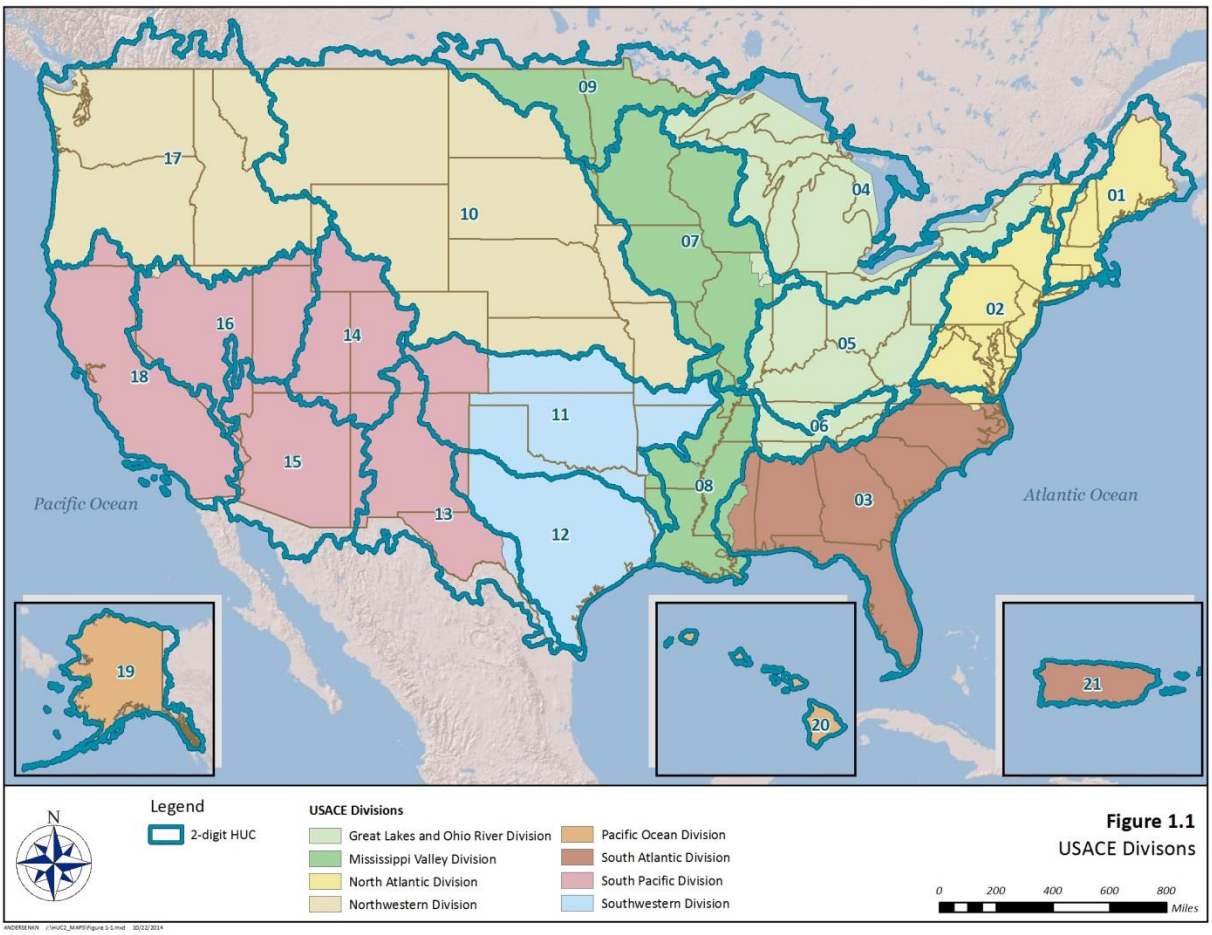

Figure 1.1. 2-digit Water Resources Region Boundaries for the Continental United States, Alaska, Hawaii, and Puerto Rico.

Figure 1.2. Water Resources Region 19: Alaska Region Boundary.

1.1 A Note on the Water Resources Region Scale

USACE and other resource management agencies require reliable, science-based methods for incorporating climate change information into the assessments that support water resources decisions and actions. Such planning assessments must quantify projections of future climate and hydrology. One common practice is to begin by developing relationships between the currently observed climate and the projected future possible climate over the assessment region.

However, the numerical models producing these multiple projections of future possible climate were not designed to support these assessments for local-to-regional scale operations. This means that intervening steps have to be taken to correct obvious biases in the models' outputs and to make the outputs relevant at the scales where hydrologic resource assessments can take place. The commonly used name for these post-processing steps is "downscaling" because one step is using one or another method to spatially (and temporally) disaggregate or interpolate (or other) the results produced at the numerical climate models' native scale to the scale of the water resources assessment. The current generation of climate models, which includes the models used to generate some of the inputs described in this work, have a native scale on the order of one to two hundred kilometers on each side of the grids used to simulate climate for Earth, substantially too coarse for the watershed assessments needed to inform resource assessment questions and decisions.

On the other hand, these questions and decisions should not be addressed with model inputs at scales so fine that they impart false precision to the assessment. False precision would appear by suggesting that the driving climate model information can usefully be downscaled, by any method, to individual river reaches and particular project locations, for example.

The approach at USACE is to consider the questions in need of climate change information at the geospatial scale where the driving climate models retain the climate change signal. At present, USACE judges that the regional, sub-continental climate signals projected by the driving climate models are coherent and useful at the scale of the 2-digit HUCs (Water Resources Region), and that confidence in the driving climate model outputs declines below the level of a reasonable trade-off between precision and accuracy for areas smaller than the watershed scale of the 4-digit HUC (Water Resources Subregion). Hence, these summaries group information at the Water Resources Regional scale both to introduce relevant climate change literature and to support the vulnerability assessments USACE is conducting at the Water Resources Subregion scale. For Water Resources Region 19, both the 2-digit and 4-digit HUC boundaries are shown in **Figure 1.2**.

2. Observed Climate Trends

Observed climate trends within the Alaska Region are presented in this section to generally characterize current, or past, climate in the study region. While the primary cause for global warming is attributed by the scientific community to human-induced increases in atmosphere levels of heat-trapping gases (Walsh et al., 2014), this section is not focused on attribution or cause (either natural or unnatural). Rather, it is specifically focused on the identification and detection of climate trends in the recent historical record. The interrelationships of Earth's climate systems are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings. When additional detail is needed, the reader is referred to the specific references cited, including the third National Climate Assessment (NCA) which includes not only regional assessments but also foundational resources related to climate science literacy.

The climate trends presented in this section are based on peer-reviewed literature on the subject of observed climate. To the extent possible, studies specific to the Alaska Region or its subregions were relied upon. A focus is placed on identified primary variables including:

- mean temperature
- extreme temperatures
- average precipitation
- extreme precipitation events
- mean streamflow

In addition to primary variables, peer-reviewed literature addressing climate change within the geographic boundary of Water Resources Region 19 or inclusive of the Region (fully or partially) revealed additional, secondary, climatic variables that have been studied such as the spring index (SI), drought indices, and soil moisture.

The results presented below show that a general consensus amongst recent peer-reviewed literature indicates a warming trend for the Alaska Region, evidenced by average temperature increases and warmer hot and cold extremes. There is a lack of consensus on precipitation trends due to geographic, topographic, and multidecadal variability. Finally, earlier snow melt due to earlier spring onset is likely occurring in some areas.

2.1. Temperature

Analyses of the observational record show warming, with rates varying over time, with season, and with location in the region. Southern and western coastal areas are strongly influenced by Pacific Ocean sea surface temperatures (SSTs), resulting in a record of alternating warmer and cooler periods superimposed over a rising temperature trend. North of the Brooks Range, Pacific Ocean SST influence is reduced and overwhelmed by the loss of Arctic sea ice, resulting in a steadier increase in temperature over time. These trends are discussed below.

Long-term temperature changes have been nonlinear, with stepwise shifts occurring in concert with changing Pacific Decadal Oscillation (PDO) regimes in the Pacific (Stewart et al., 2013). The PDO is a climate phenomenon that results in an increase in southerly flow and warm air advection into the Alaska Region during the winter during a positive shift, resulting in mostly

positive temperature anomalies. Annual departures from the long-term mean were predominantly negative (cool) from 1949 to 1976, and mainly positive (warm) following the shift to a positive PDO regime in 1976/1977. Since the rapid warming of 1976/1977, little additional warming is reflected in statewide mean annual temperatures (Stewart et al., 2013).

Recent temperature changes have reversed some of these gains. The PDO shifted from positive to negative in 2006/2007. This shift has led to a cooling trend across most of Alaska over the subsequent five years, averaging a 1.3 °C (2.3 °F) decrease throughout the state, a trend that is statistically significant at the 90 percent confidence interval (Wendler et al., 2012). However, north of the Brooks Range, temperatures have continued to increase, rising by as much as 1.5 °C (2.7 °F) near the City of Barrow, AK. The continued rise at Barrow, AK is considered to be evidence for Arctic amplification in an area where PDO regime shifts exert little influence due to the Brooks Range (Wendler et al., 2012). **Figure 2.1** shows the diversion of annual average temperatures from the long-term mean for 20 stations located throughout the Alaska Region. The PDO shift is apparent in the late 1970s and the recent cooling trend can be seen in the final five years of records.

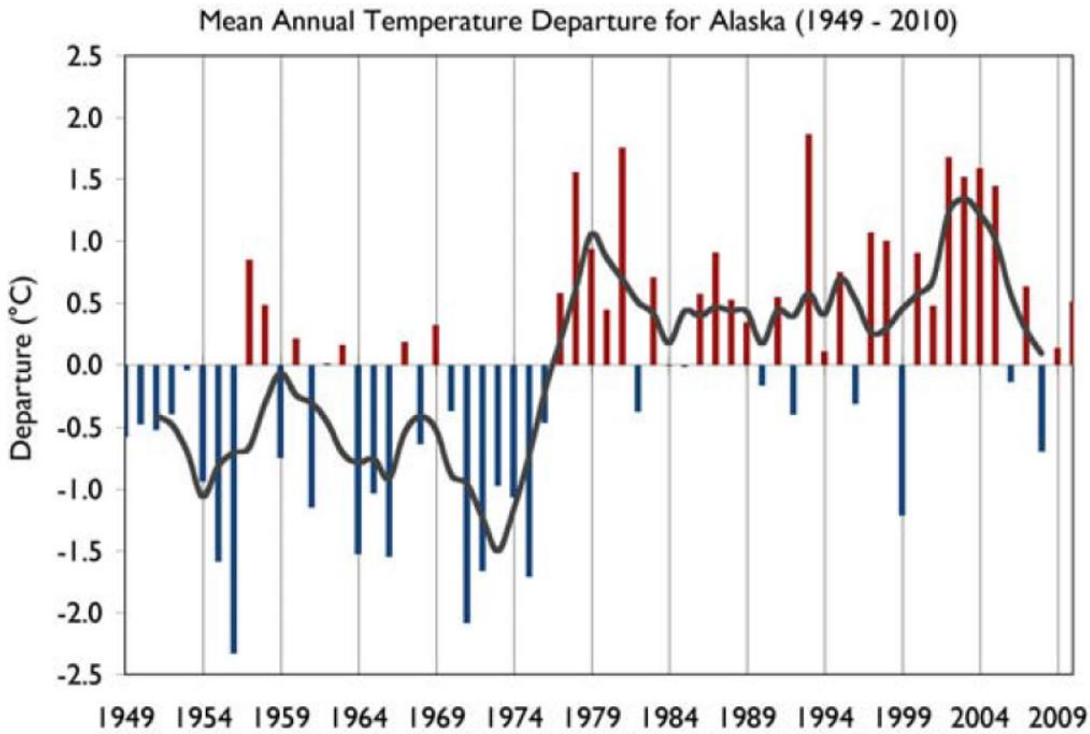

Figure 2.1. Temperature deviation from the long-term mean, average of the 20 first order stations, Alaska 1949-2010 (Wendler et al., 2012).

Warming has not been linear, Wendler et al. (2012) also examined the relationship between the recent temperature patterns and various circulation indices (such as the PDO). These indices are well-documented and cyclical, and not tied to carbon emissions. The authors found strong correlation with several indices, indicating that the historic trends may be influenced by natural decadal variations (**Table 2.1**). The authors conclude that, "the long term observed warming of Alaska is about twice the global value, as expected by the increasing CO_2 and other trace gases, is sometimes temporarily modified or even reversed by natural decadal variations" (Wendler et al., 2012).

Table 2.1. Averaged mean annual temperature deviation from the norm against different circulation indices for the first decade of the 21st century (Wendler et al., 2012).

Index	Abbreviation	Correlation Coefficient (r)
Pacific Decadal Oscillation	PDO	0.76
East Pacific/N.P. Pattern	EP/NP	0.73
Southern Oscillation Index	SOI	-0.66
El Nino	NIN 04	0.63
El Nino	Nino 3.4	0.50

Other authors have also studied trends in temperature changes throughout Alaska, with the majority reporting an overall warming trend. Polyakov et al. (2002) analyzed regional temperature trends at 75 stations over 125 years (1875-2000). The temperature records for Fairbanks, in interior Alaska, span a century and show 1.4 °C (2.5 °F) warming (statistical significance was not noted). This is about twice the widely reported global value attributed to climate change (Hansen et al., 2006).

Hinzman et al. (2005) similarly discovered a warming trend at several individual climate stations when examining records from 1880 to 2000. **Figure 2.2** shows the station trends and statistical significance of linear increases in annual mean temperature.

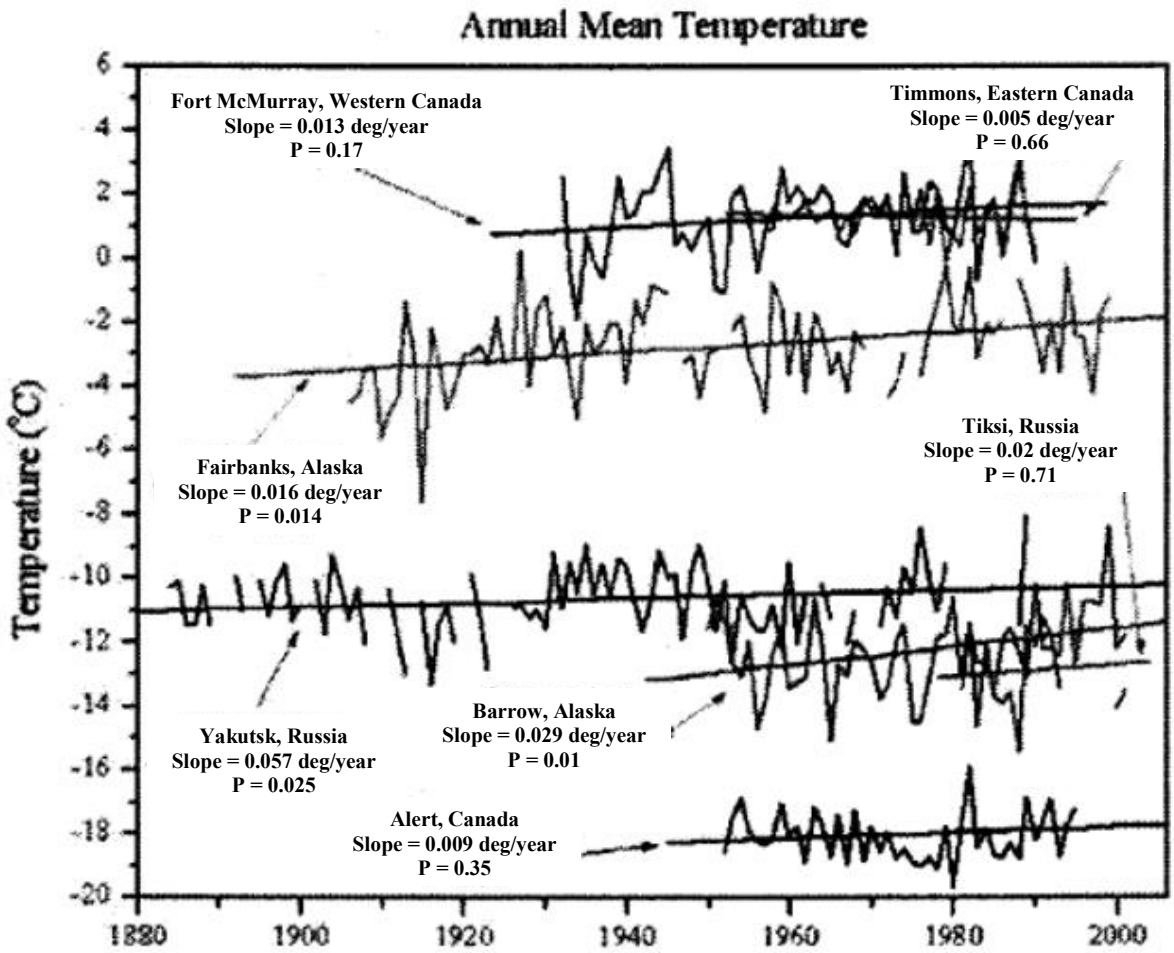

Figure 2.2. Climate stations around the Arctic, selected primarily for long timeseries, demonstrate increasing trends in air temperature. The p-values are shown; lower p-values indicate greater statistical significance of the linear trend (p-value of 0.01 implies the slope of the trend line is significantly different from zero at the 99 percent confidence level) (Hinzman et al., 2005).

In addition to the work described above, attributing recent temperature trends to the PDO shift and other circulation indices, Wendler and Shulski (2009) also studied longer term temperature trends in Fairbanks, AK. Their findings are in accord with the 1.4 °C (2.5 °F) warming trend over the 20th century reported by Polyakov et al. (2002). **Figure 2.3** shows the time series of temperature data and best linear fit used to draw this conclusion. The authors did not report the statistical significance of this trend.

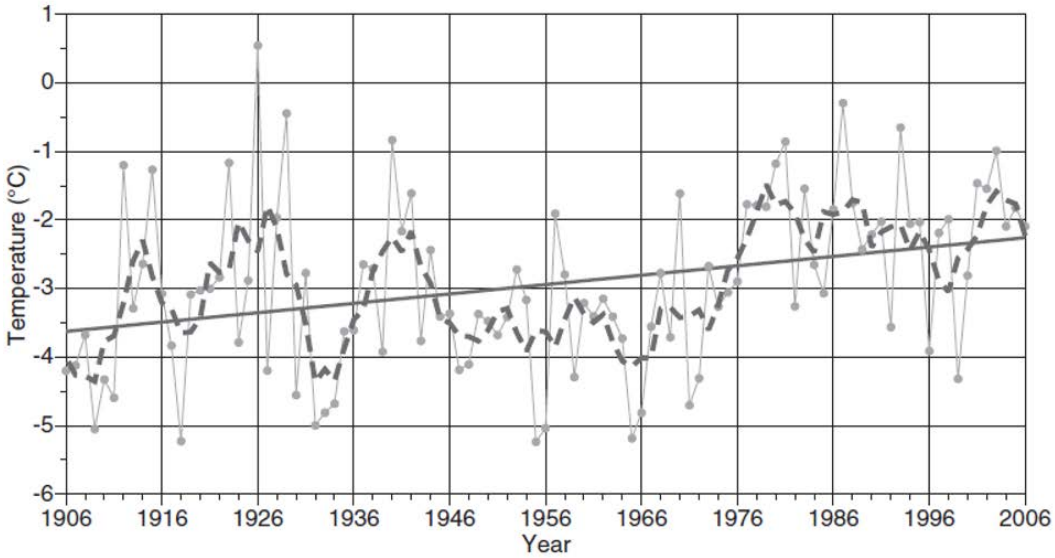

Figure 2.3. Time series of mean annual temperatures at Fairbanks, AK from 1906 to 2006. The points represent the annual values. The dashed line represents the five-year running mean. The solid line represents the best linear fit (Wendler and Shulski, 2009).

The upward temperature trend has not been observed to be uniform throughout the year. Wendler and Shulski (2009) compared trends in winter (October to April) to those in summer (May to September). They found that winter has been warmer, spring and summer have been slightly warmer, and fall, slightly cooler, resulting in a net upward temperature trend. Arendt et al. (2009) found similar seasonal trends, finding positive, statistically significant trends in winter and summer after examining temperature data from 67 climate stations in and around the Alaska Region from 1950 to 2002 (**Figure 2.4**).

The rate of season warming appears to be greater in the interior and northern areas of the Alaska Region than in areas to the south and west. Over the period 1949-2011, the greatest warming has been in the winter (December to February), with the interior and arctic areas of the Alaska Region warming by as much as 3.7 to 5 °C (6.7 to 9 °F) while the south-central and southeastern coastal areas warming from 0.7 to 3.6 °C (1.3 to 6.5 °F) (statistical significance was not noted) (Stewart et al., 2013). The amount of temperature change is less in the remaining three seasons, with slight cooling observed in the fall (September to November). The exception to this pattern is the arctic area, where the temperature increase in Barrow, AK is least in summer (June to August).

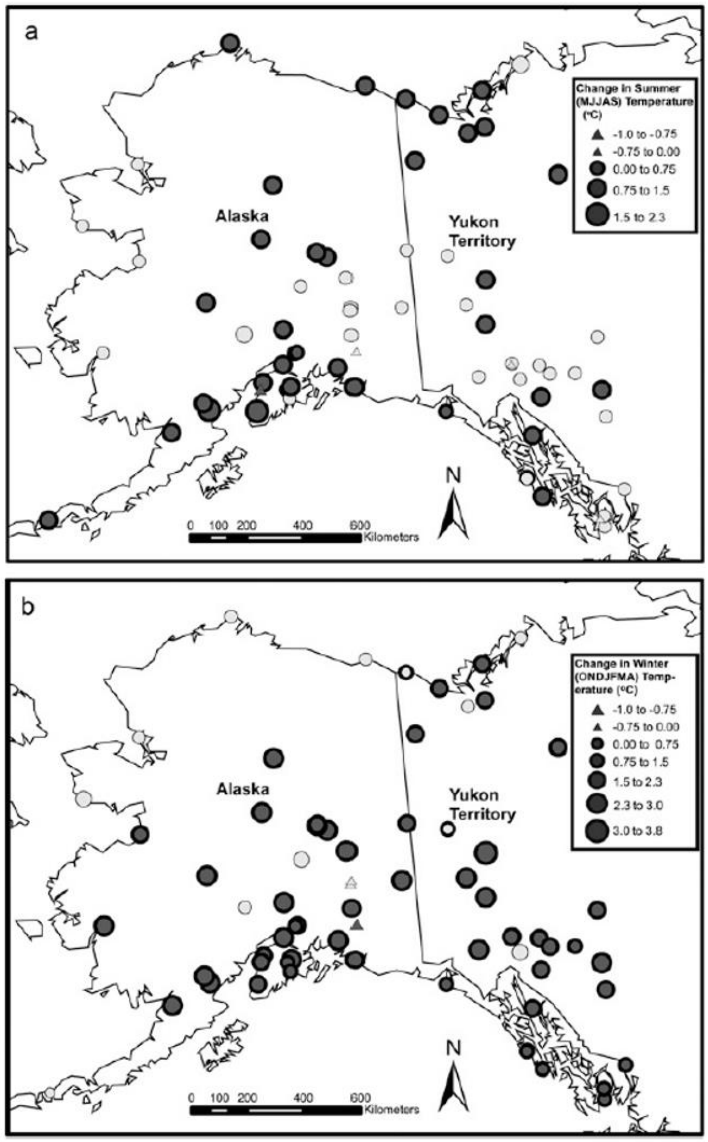

Figure 2.4. Changes in average (a) summer and (b) winter air temperature, 1950 to 2002. Black symbols represent changes significant at $p < 0.05$ (Arendt et al., 2009).

Stafford et al. (2000) also found that the recent warming trend, from 1948 to 1998, has been concentrated more in the winter than in other seasons. **Figure 2.5** shows their findings of change in mean temperature for winter (December to February), spring (March to May), summer (June to August), and fall (September to November). Increases were observed in all seasons except for fall.

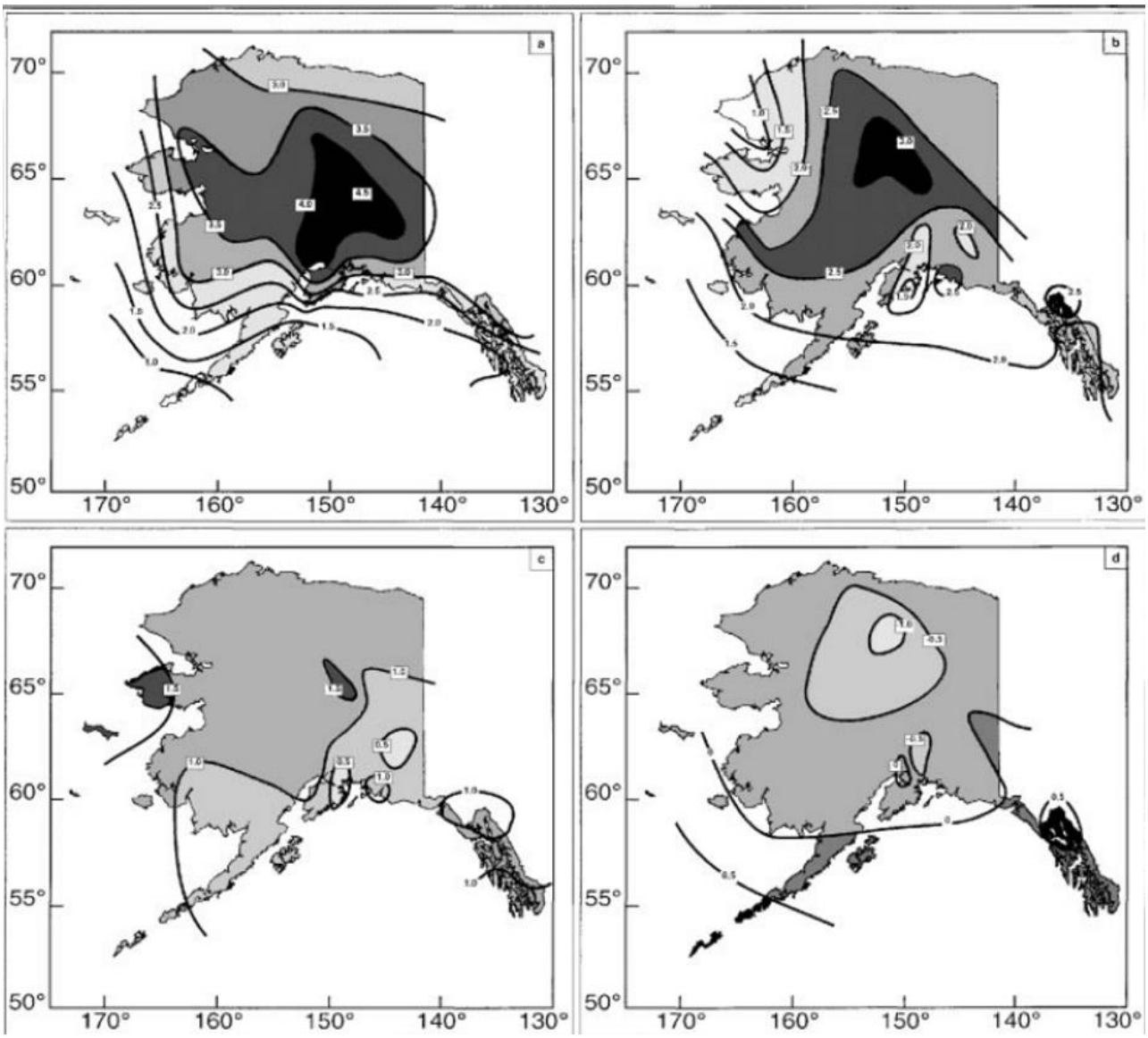

Figure 2.5. Change in mean temperature (°C) for seasonal temperatures over the 50-year period from 1949 to 1998, for (a) winter, (b) spring, (c) summer, and (d) fall. Darker colors indicate a larger positive change. Dark lines are shown at 0.5 °C intervals (Stafford et al., 2000).

In addition, Markon et al. (2012) reported increasing annual average temperatures over a similar time period, 1949 to 2005, and focused on the seasonal trend differences. They found that the average annual statewide temperature in Alaska has increased 4 °F (2.2 °C), with the bulk of the increases occurring in winter (6.3 °F or 3.5 °C) and spring (4.1 °F or 2.3 °C). Summer and fall showed 2.3 °F (1.3 °C) and 1.4 °F (0.8 °C) increases, respectively.

In an attempt to better quantify geographic and seasonal temperature trends, Bieniek et al. (2014) used observational data from 163 weather stations to examine temperature trends over the period 1920 to 2012 for the recently developed climate divisions in Alaska (Bieniek at al. 2012). Despite strong influence from the PDO, producing an alternating warming and cooling trend, an underlying steady increase of approximately 1 °C (1.8 °F) is observed statewide over the last 100

years. Warming is greatest in the northeast interior and north slope areas (1.8 °C and 1.6 °C [3.2 °F and 2.9 °F], respectively), and least in the southern coastal areas and southeast. Coastal regions along the Bering Sea and Pacific Oceans are strongly influenced by the PDO phase. In recent decades, north slope temperature variations have become asynchronous with the PDO, reflecting the influence of Arctic sea ice loss. Not surprisingly, the greatest differences in temperature in the north slope area occur in autumn, coincident with the seasonal sea ice minimum.

For the period of 1920-2012 (Bieniek et al., 2014), statewide increases in temperature occurred in all months except October and November, with the greatest increase in December, February, April, May and July. A warming trend in all months (although weakest in November) occurs in the north slope area. Long-term cooling over the summer months is evident throughout the panhandle region.

Extreme cold and warm temperature trends have followed the same overall warming pattern as average annual temperature trends based on studies of the past 100 years of record. For the U.S. Climate Change Science Program Synthesis and Assessment Product, Kunkel et al. (2008) determined that there is an increasing trend in the number of days in a year when the daily low temperature is unusually warm. **Figure 2.6** shows the results of this analysis and that the trend is statistically significant in the Alaska Region.

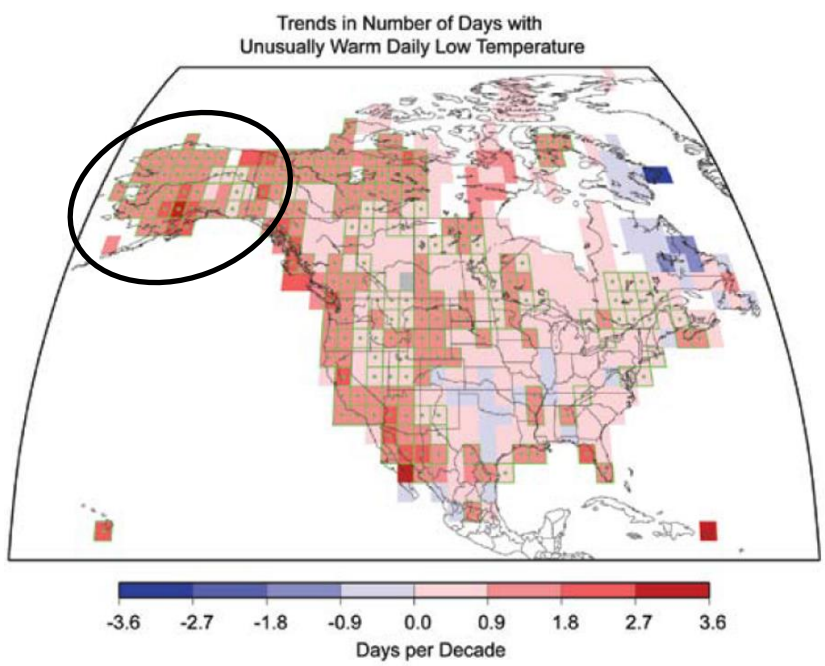

Figure 2.6. Trends in the number of days in a year when the daily low is unusually warm (i.e., in the top 10 percent of warm nights for the 1950 to 2004 period). Grid boxes with green squares are statistically significant at the p = 0.05 level. Alaska is within the black oval (Kunkel et al., 2008).

Wendler and Shulski (2009) also analyzed trends in observed temperature extremes, reporting a decrease in the number of days below -40 °C between 1906 and 2006 at Fairbanks, AK. The decrease from 14 to 8 days annually is not linear, as the drop in extremely cold days seems to

coincide with the PDO shift in the 1970s (**Figure 2.7**). The authors did not see a trend in the number of days per year above 26.7 °C (80 °F), considered extremely warm for Alaska.

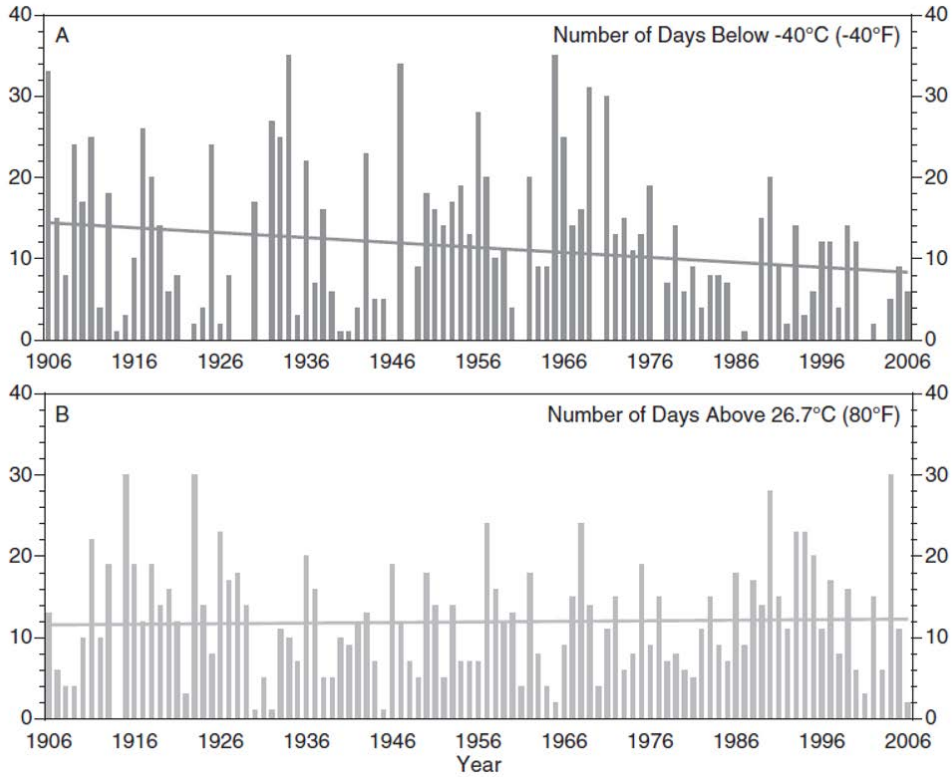

Figure 2.7. Frequency of occurrence of (A) very cold days and (B) very warm days for Fairbanks, AK. The lines represent best linear fit (Wendler and Shulski, 2009).

Wendler and Shulski (2009) also reported an increase in the length of the growing season in Fairbanks, defined as the time period each year when the temperature in summer never dips below the freezing point. **Figure 2.8** shows the increasing trend based on two definitions of the freezing point for plants (0 and -2.2 °C). An earlier spring and later fall contributed equally to the 27 to 45 percent increase in growing season length (depending on the definition of freezing point).

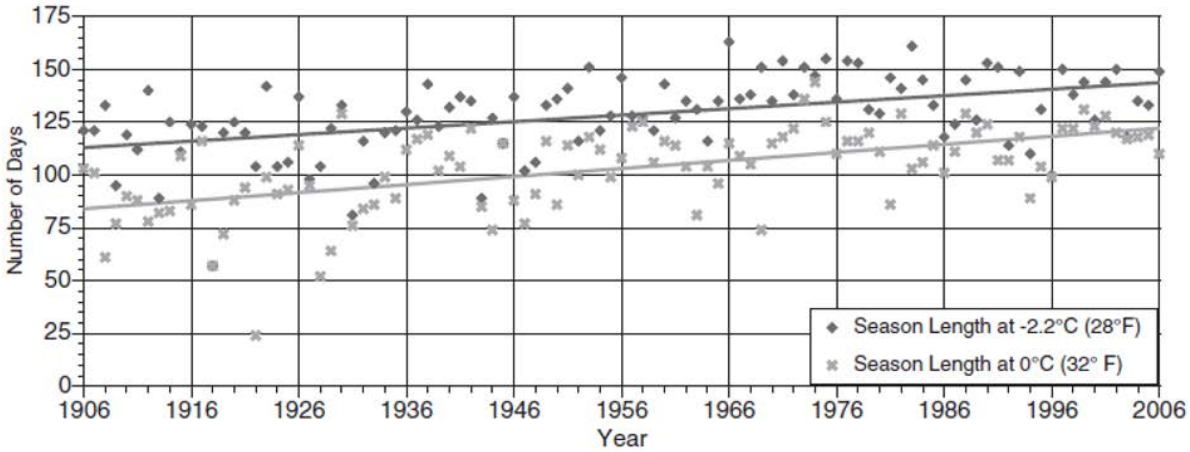

Figure 2.8. Length of the growing season in Fairbanks, AK, 1906 to 2002. Light gray/dark grey markers represent the number of days when the temperature remained above 0/-2.2°C. The lines represent the best linear fit (Wendler and Shulski, 2009).

Markon et al. (2012) found an increase in both warm and cold extremes for 26 stations throughout the different regions of Alaska, using data from 1950 to 2008. All stations in all regions except the southeast showed upward trends in occurrence of warm extremes (top 1 percent of temperatures) and downward trends in occurrence of cold extremes (bottom 1 percent of temperatures). In the southeast, 71 and 86 percent of stations showed the warm and cold extreme trends, respectively. Information on the statistical significances of these trends was not provided.

Peterson et al. (2013) reported a similar pattern for Alaska using data from 1950 to 2010 from throughout the U.S. They found that the decadal average values of heat wave and cold wave indices have been trending warmer, with both an increasing heat wave index and decreasing cold wave index. The indices are a normalized metric of the number of extreme temperature events of 4-day duration. An event is considered extreme if the average temperature exceeds the threshold for a 1- in 5-year recurrence. **Figure 2.9** shows the index trends for the contiguous U.S. and Alaska.

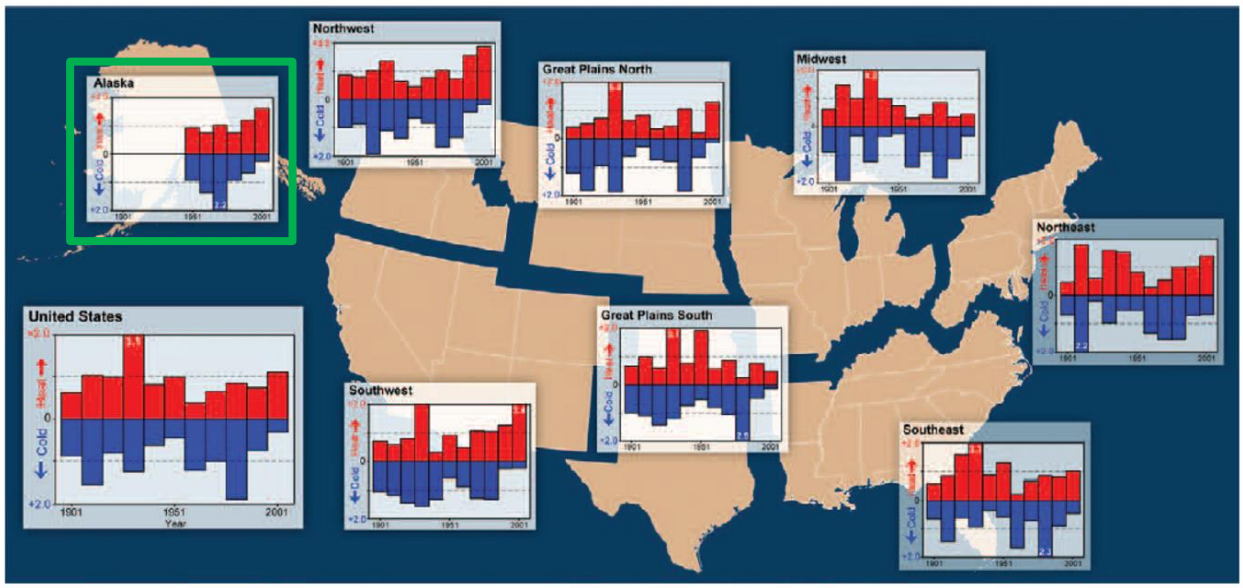

Figure 2.9. Time series of decadal average values of heat wave (red bars) and cold wave (blue bars) indices. Longer bars indicate a greater number of heat/cold waves in that decade. The Alaska region graph is within the green box (Peterson et al., 2013).

Key point: A general consensus amongst recent peer-reviewed literature indicates a warming trend for the Alaska Region, especially in the winter and spring seasons. The trend is evidenced by warmer average winter temperatures, warmer average annual temperatures, and earlier spring onset/longer growing season observations. Extreme cold temperatures have become less frequent while extreme warm temperatures have become more frequent. An important consideration when discussing the most recent 40-year warming trend is the apparent shift in the PDO, a circulation index that has historically impacted Alaskan temperatures, perhaps independently from global climate change processes. In recent decades, warming in the north slope area has been asynchronous with changes in PDO, likely a result of sea ice loss in the Arctic sea and resulting greater summer heat storage in the open water.

2.2. Precipitation

Precipitation in Alaska is highly variable and displays little multidecadal variability or consistent geographic patterning by region or climate division within Alaska. The detection of trends is strongly influenced by the selection of start and end dates, changes in instrumentation, and choice of dataset. Different studies report different trends statewide and by region. Some evidence suggests an increase in the occurrence of extreme precipitation events.

In the third NCA report, Walsh et al. (2014) report that there is no long-term statewide trend in precipitation over the last century compared to the average for 1901-1960 (**Figure 2.10)** based on the revised NOAA National Climate Data Center (NCDC) data. The authors compared the average precipitation change by decade compared to the 1901 to 1960 average.

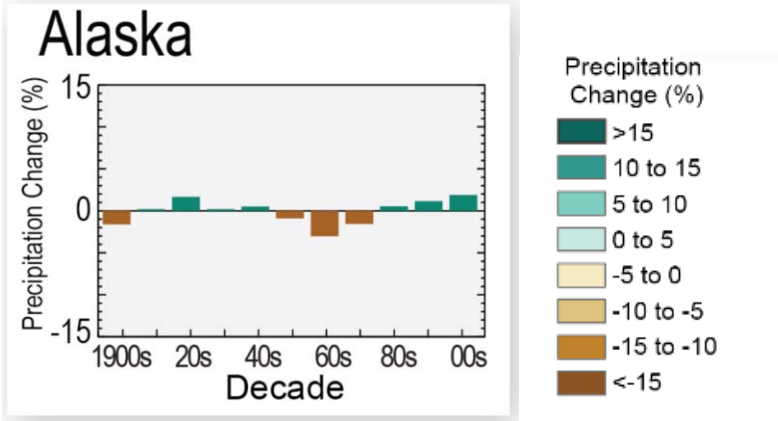

Figure 2.10. Average precipitation changes by decade compared to the 1901 to 1960 average. The far right bar in each graph is for 2001-2012. (Walsh et al., 2014, adapted from Peterson et al. 2013).

Using the same NCDC precipitation data, Walsh et al. (2014) show no trend in the annual amount of precipitation falling in very heavy events (the heaviest 1 percent of all daily events) from the 1951-2001 for the Alaska Region, relative to the 1951-1980 average. However, the authors reported an 11 percent increase for the Alaska Region for the amount of precipitation falling in those very heavy events. These trends are reported to be larger than natural variations. (**Figure 2.11).**

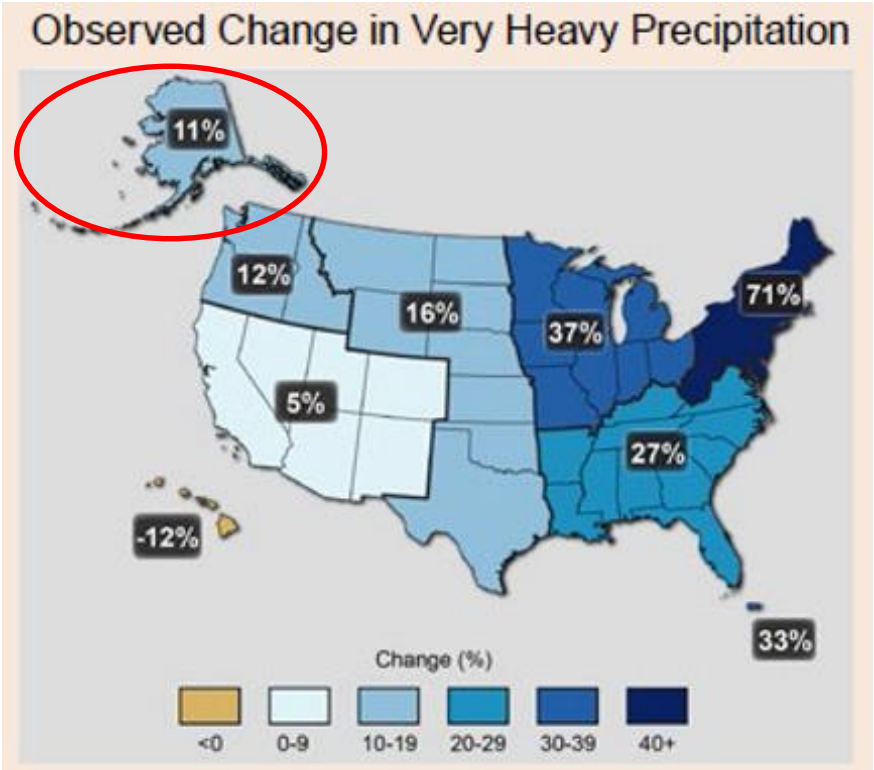

Figure 2.11. Percent increases in the amount of precipitation falling in very heavy events (defined as the heaviest 1 percent of all daily events) from 1958 to 2012. The Alaska Region is shown within the red oval (Walsh et al., 2014).

Stafford et al. (2000) analyzed 25 weather stations throughout Alaska to determine observable trends from 1948 to 1998. The authors found different precipitation trends for different latitudes within the region (**Table 2.1**). They reported an increasing trend in annual precipitation for all areas except the Arctic. Fall (or autumn) and winter show the highest seasonal increases for all areas except the Arctic. The greatest decrease in precipitation was observed in the Arctic winter: -106 percent. The time series of observed precipitation for Barrow, AK, which is representative of the Arctic area is shown in **Figure 2.12**. The decreasing linear trend line is statistically significant at the 95 percent confidence interval.

Table 2.1. Change in precipitation, percent, from 1949 to 1998 for areas within Alaska (Stafford et al., 2000).

	Annual	Winter	Spring	Summer	Autumn
South/Southeastern	10	22	12	−1	10
Western	9	25	17	−11	21
Interior	7	3	6	1	19
Arctic	−36	−106	−57	−16	−36

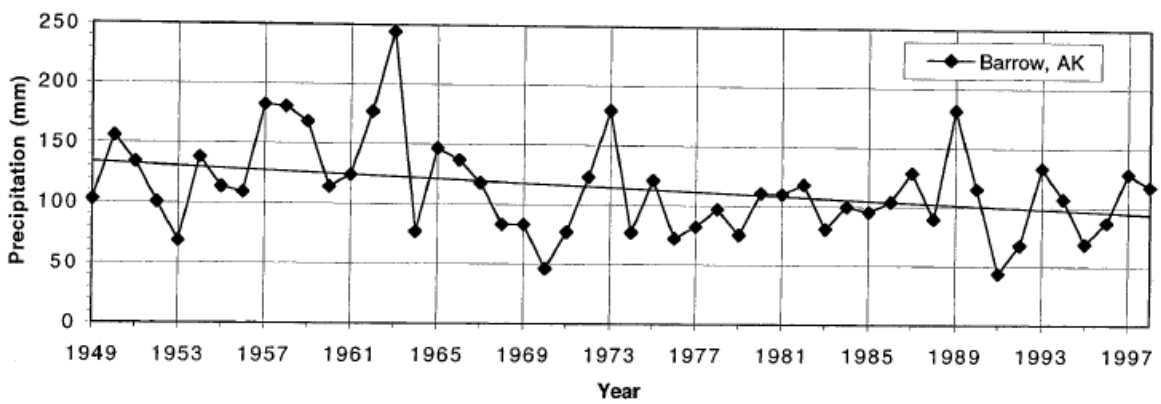

Figure 2.12. Time series of annual precipitation for Barrow, AK with a linear least squares regression line (Stafford et al., 2000).

Hinzman et al. (2005) performed a similar trend analysis on historical annual precipitation data from multiple stations in the Arctic region, some outside Alaska, for the past century. The authors discovered similar variability in the trends, but generally saw increasing trends at most stations. Several stations, some outside Alaska, showed statistically significant linear trends. The two stations shown within the region show split trends – increasing annual precipitation for Fairbanks, AK and decreasing for Barrow, AK. **Figure 2.13** shows the time series for multiple climate stations analyzed in the study.

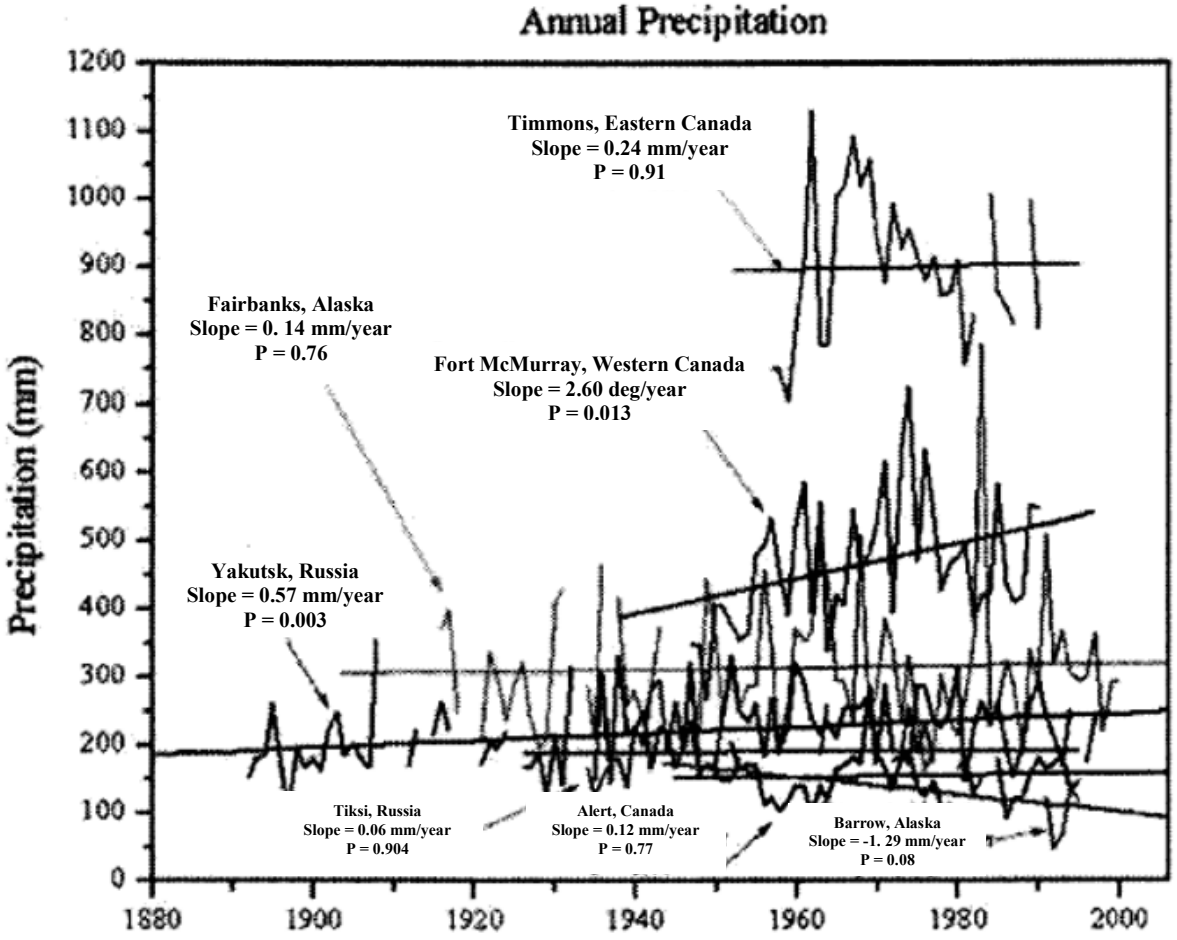

Figure 2.13. Precipitation time series for arctic climate stations. Only Fort McMurray, Canada and Yakutsk, Russia display strongly significant trends (Hinzman et al., 2005).

Wendler and Shulski (2009) discovered a similar decreasing trend in precipitation totals for a climate station in Fairbanks, AK. They reported an 11 percent decrease in precipitation (not statistically significant) for the 90-year period 1916 to 2006 (**Figure 2.14**). The decrease is strongest in the spring, followed by winter. The decrease is small in summer, when almost one-half of the annual precipitation occurs. No change was observed for the fall season.

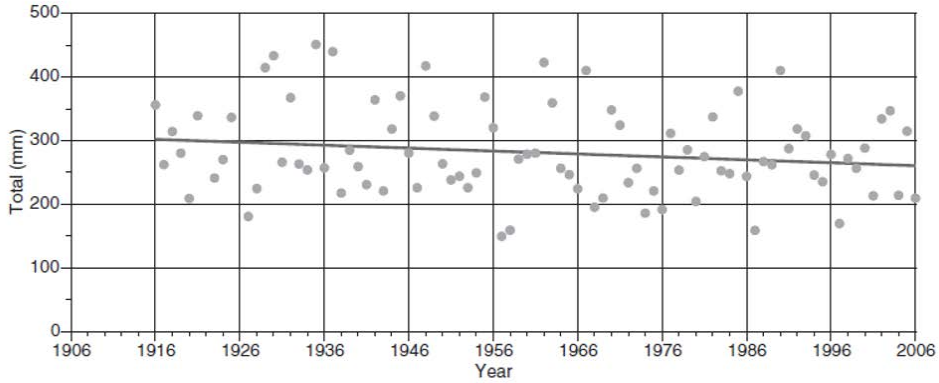

Figure 2.14. Time series of the annual precipitation values for Fairbanks, AK. The solid line represents the best linear fit (not statistically significant) (Wendler and Shulski, 2009).

Arendt et al. (2009) examined precipitation data from 1950 to 2002 and reported mixed trends at Alaskan sites. **Figure 2.15** shows the change in total annual precipitation over that time. Most sites show an increasing trend, but the trends are statistically significant at only three sites. Several southern and central sites show a decreasing trend, but only one site is statistically significant. The reported annual changes are generally +/- 375 mm/year, except at one site in the far southern coastal region which showed a statistically significant upward trend of 1,125 to 1,500 mm/year.

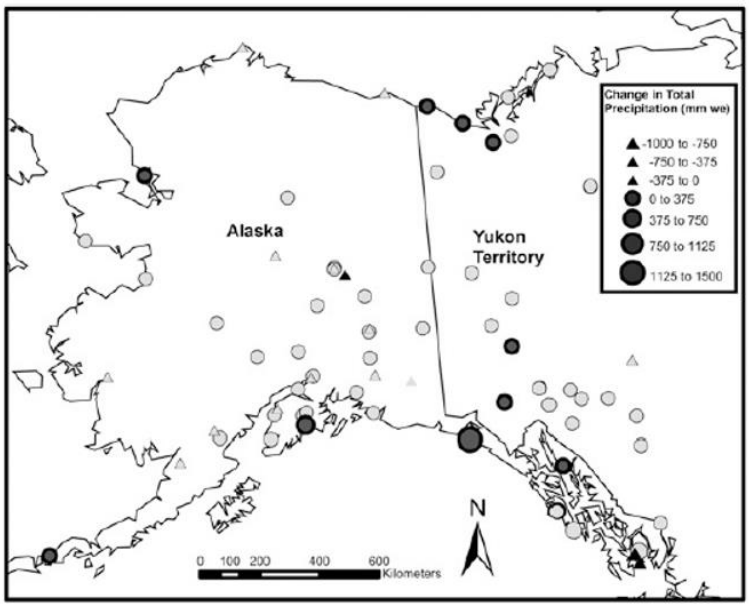

Figure 2.15. Changes in annual total precipitation, 1950 to 2002. Black symbols represent changes significant at $p < 0.05$ (Arendt et al., 2009).

Bieniek at al. (2014) reported no trends in precipitation across the period 1920-2012. Sites in the southern part of Alaska and the panhandle showed some multidecadal variation in precipitation quantity, while the north slope showed multidecadal variation when precipitation was analyzed as the percent of average. The authors conclude that the spatial and temporal patterns are strongly conditioned by variation in the position of the dominant storm track across the region. No clear regional or statewide trends in precipitation were observed in the data, and the detection of trends was strongly influenced by the choice of analysis start and end dates.

Sensitivity of precipitation trend detection to the analysis starting and ending dates, as well as to changes in instrumentation, were examined by McAfee et al. (2013). They found that these changes make it difficult to accurately detect the influence of multidecadal climate variablility and to assess historical precipitation trends in Alaska. The study was able to detect an increase in precipitation at Barrow, AK and some drying in the south-central portion of the state through 2010 (these trends are the reverse of those reported above, including those by Arendt et al. (2009). Wendler and Shulski (2009), and Hinzman et al. (2005)). Analysis of gridded precipitation data sets for Alaska showed sensitivity to dataset selection that strongly affected the direction of precipitation trends in Alaska (McAfee et al., 2014).

Markon et al. (2012) reported similar patterns as Arendt et al. (2009). While the observed annual precipitation trends have been highly variable from 1949 to 2005, the authors report an overall 10 percent increase in precipitation throughout Alaska. Regionally, the trends are different, with precipitation decreases apparent in the northern/Arctic areas. As shown in **Table 2.2**, and in agreement with Walsh et al. (2014), many climate stations showed an increasing trend in the frequency of extreme events. The two publications may have used the same data to draw their conclusions about the increasing trend.

Table 2.2. Percentage of stations in each region in Alaska displaying upward trends in occurrence of extreme 3-day precipitation events from 1950 to 2008 (Markon et al., 2012).

Region	Winter (percent)	Spring (percent)	Summer (percent)	Fall (percent)
Arctic[1]	0	0	0	0
West central	67	100	0	67
Interior	33	50	50	50
Southwest	50	25	25	75
South central	40	40	40	60
Southeast	71	57	43	57

[1]Only one station in the Arctic region (Barrow) had sufficient data for this analysis.

Stewart et al. (2013) reported no significant change in the overall frequency of strong storm events, though the northern and northwestern coasts have seen a significant increase in the occurrence of strong storms when a protective sea ice cover is not present during the summer and fall.

Key point: Peer reviewed studies have shown both increasing and decreasing trends in annual total precipitation throughout the Alaska Region. The lack of consensus may reflect lack of trends, or ongoing challenges with data measurement and analysis. There is better consensus that precipitation may be becoming concentrated in larger storm events.

2.3. Hydrology

Few studies have reported on observed historic trends in hydrology in the Alaska Region. Stewart et al. (2004) and Stewart et al. (2005) studied the changes in timing of streamflow due to changing snow melt patterns. Their research included stations in southern Alaska. **Figure 2.16** shows the observed change in timing of the centroid of annual streamflow from 1948 to 2000. The streamflow centroids for Alaska stations have shifted between 5 and 20 days earlier, with 6 out of 15 stations showing statistically significant trends at the 90 percent confidence level.

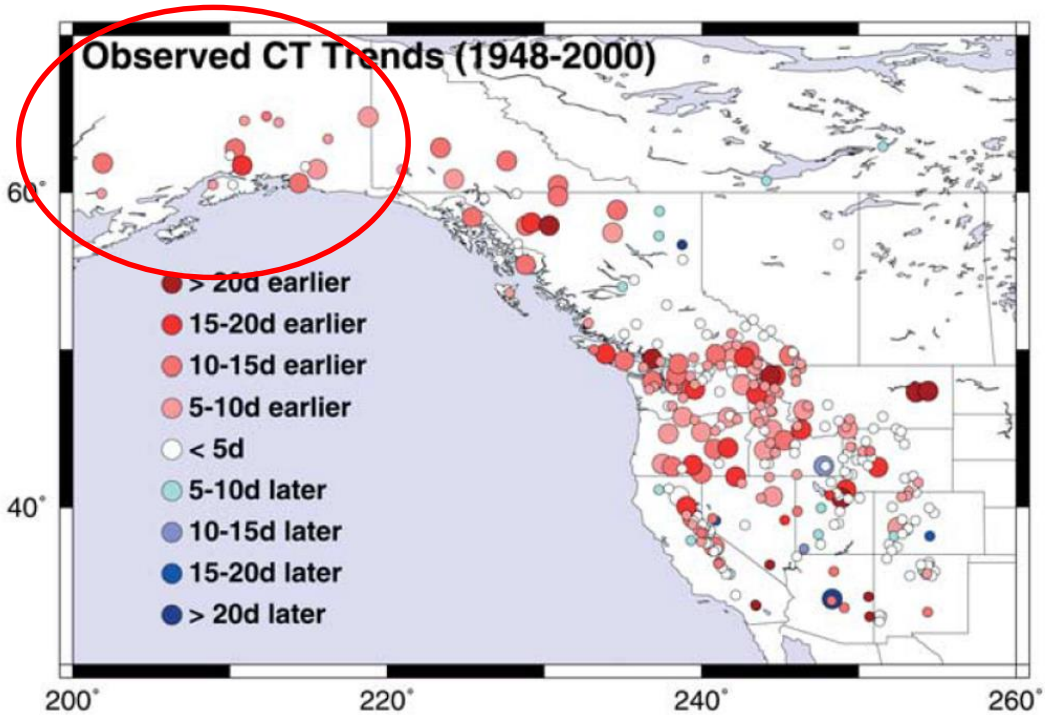

Figure 2.16. Observed changes in the timing of the center of mass of flow (CT). Color of the symbols corresponds to a given magnitude of the linear trend, which is given in terms of the corresponding shift (days) for the 1948 to 2000 historical period. Larger circles indicate statistically significant trends at the 90 percent confidence level. A portion of the Alaska Region is shown within the red oval (Stewart et al., 2004; Stewart et al., 2005).

A second study by Brabets and Walvoord (2009) reviewed streamflow trends in the Yukon River Basin (YRB) from 1944 to 2005. The study focused on streamflow responses to the PDO shift, but the results are relevant to review for the purposes of observed climate change. Their findings show that most sites on the YRB have seen a statistically significant increase in winter flow (January to March) and April flow, likely due to an increase in groundwater flow. There have been some negative trends for June and July in the upper and middle YRB. No annual trends were observed.

Key point: There have not been many studies on observed changes in hydrology in the Alaska Region. Earlier snow melt due to earlier spring onset is most likely occurring in some areas.

2.4. Summary of Observed Climate Findings

A general consensus amongst recent peer-reviewed literature indicates a warming trend for the Alaska Region, especially in the winter and spring seasons. Extreme cold temperatures have become less frequent while extreme warm temperatures have become more frequent. Peer-reviewed studies have shown both increasing and decreasing trends in annual total precipitation throughout the Alaska Region. There have not been many studies on observed changes in hydrology in the Alaska Region. Earlier snow melt due to earlier spring onset is most likely occurring in some areas.

3. Projected Climate Trends

While historical data is essential in understanding current and future climate, nonstationarity in the data (i.e., a changing climate) dictates the use of supplemental information in long-term planning studies. In other words, the past may no longer be a good predictor of the future (Milly et al., 2008). Consequently, the scientific and engineering communities have begun using computer models of the Earth's atmosphere and associated thermodynamics to project future climate trends for use in water resources planning efforts. While significant uncertainties are inherent in these model projections, the models, termed Global Climate Models (GCMs), are widely accepted as representing the best available science on the subject, and have proven highly useful in planning as a supplement to historical data. A wealth of literature now exists on the use of GCMs across the globe.

This section summarizes projected climate trends, as projected by GCMs, within the Alaska Region identified in a review of recent peer-reviewed literature. The information presented should be considered an overview and, similar to Section 2 on observed climate trends, does not focus on attribution or causation of the projected climate trends or the causal relationships between climate variables. These relationships are complex and influenced by multiple natural and unnatural (i.e., anthropogenic greenhouse gas emissions) forcings that influence the Earth's climate system. Typical of projected climate studies, often specific (and sometimes multiple) greenhouse gas emission scenarios (or representative concentration pathways) are modeled by a single GCM (or ensemble of GCMs). The spectrum of scenarios offer a wide range of "climate futures" so each study's assumed emission scenario(s) are noted. When additional detail is needed, the reader is referred to the specific references cited, including the third NCA which includes not only regional assessments, but also foundational resources related to climate science literacy, GCMs, and emission scenarios.

The USACE vulnerability assessments (https://corpsclimate.us/rccvar.cfm) rely on downscaled climate projection data and hydrologic simulations produced by USACE in conjunction with Lawrence Livermore National Laboratory, Bureau of Reclamation, U.S. Geological Survey, Climate Central, Scripps Oceanographic Institute and Santa Clara University, and others. The data are housed in the publicly accessible Downscaled Climate and Hydrology Projections website archive, hosted by Lawrence Livermore National Laboratory, which is meant to provide access to climate and hydrologic projections at spatial and temporal scales relevant to watershed

or basin-scale water resources management decisions. These data, and the vulnerability assessments for which they provide a foundation, serve as supplements to the information about projected climate conditions provided in this report.

Results of this review indicate that there is a consensus in the scientific literature that air temperatures, precipitation amounts, and runoff will trend upwards over the next century in the Alaska Region.

3.1. Temperature

The third NCA reports that, depending on the greenhouse gas emissions scenario, average temperatures in Alaska are projected to rise between 3 °F (1.7 °C) and 15 °F (8.3 °C) in the later part of this century (2071 to 2099) as compared to the later part of last century (1970 to 1999) (Walsh et al., 2014). **Figure 3.1** shows the projected increase for four future scenarios and shows that the warming is projected to increase from south to north.

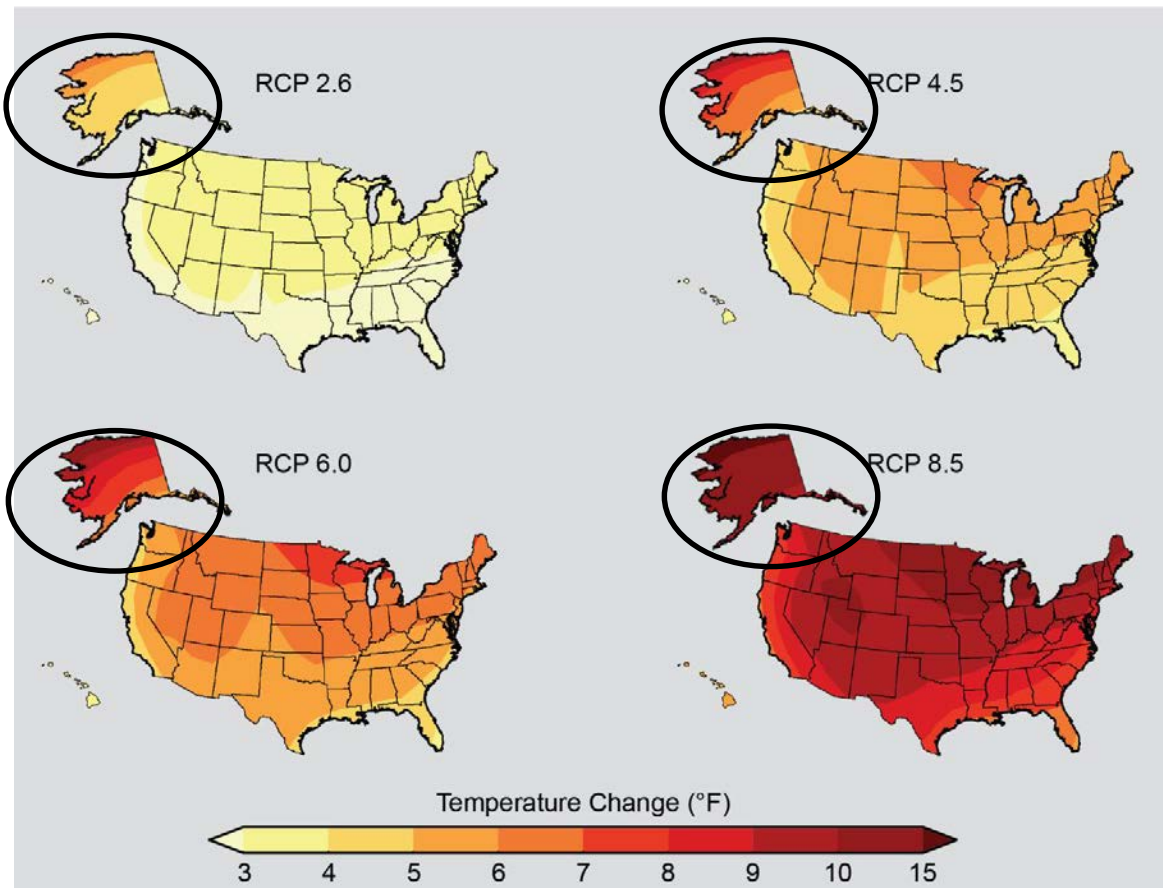

Figure 3.1. Projections show change in average temperature in 2079 to 2099 relative to 1970 to 1999. The scenarios shown are as follows: RCP 2.6 (rapid emissions reductions, more than 70 percent cuts from current levels by 2050 and further large decreases by 2100); RCP 4.5 and 6.0 (intermediate emission cuts); and RCP 8.5 (continued emissions increases). The Alaska Region is within the black oval (Walsh et al., 2014).

The third NCA also presents future modeling results suggesting warming of extreme temperatures in the Alaska Region. **Figure 3.2** presents modeling results from two emissions scenarios for 2081 to 2100 extreme temperature predictions, as compared to a 1986 to 2005 baseline. The average of the coldest days in Alaska during the future period are predicted to be from 4 °F (2.2 °C) to 9 °F (5 °C) warmer under the rapid emission reduction scenario and over 15 °F (8.3 °C) warmer under the continued emission increase scenario. The average of the hottest days during the future period are predicted to be up to 3 °F (1.7 °C) warmer under the rapid emission reduction scenario and from 7 °F (3.9 °C) to more than 15 °F (8.3 °C) warmer under the continued emission increase scenario.

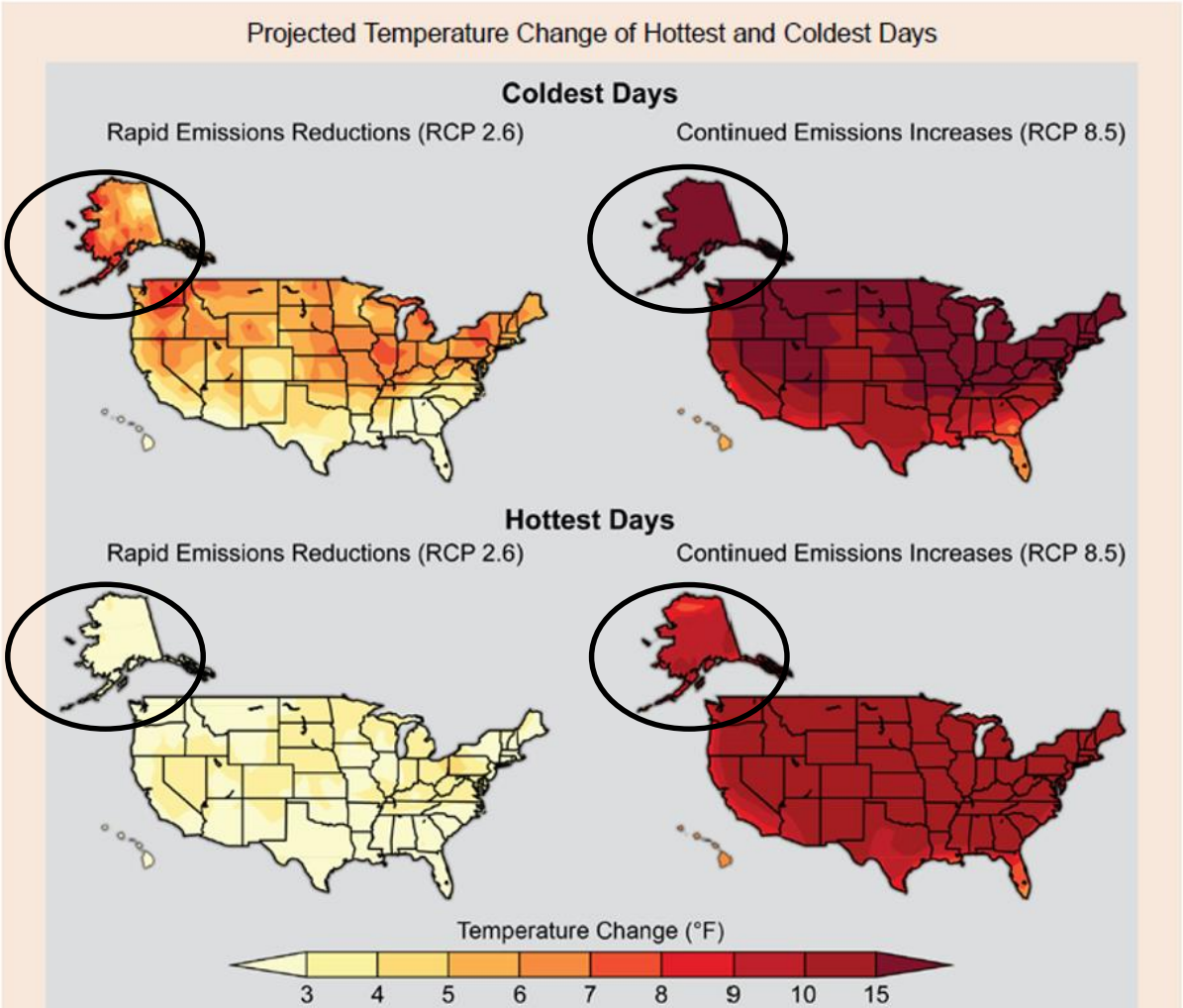

Figure 3.2. Change in surface air temperature at the end of this century (2081-2100) relative to the turn of the last century (1986-2005) on the coldest and hottest days under the RCP 2.6 scenario and a scenario that assumes continued increases in these gasses (RCP 8.5). This figure shows the estimated changes in the average temperature of the hottest and coldest days in each 20-year period. The Alaska Region is within the black oval (Walsh et al., 2014).

Other recent publications have drawn similar conclusions about the future of temperature trends in the Alaska Region. Stewart et al. (2004) and Stewart et al. (2005) looked at temperature projections to determine how changing snow melt patterns may influence streamflow timing. They report the results of three different future climate model ensembles that suggest southern Alaska may see an average annual temperature increase of 5 °C (9 °F) in 2070 to 2099 relative to the 1951 to 1980 historical simulations (**Figure 3.3**).

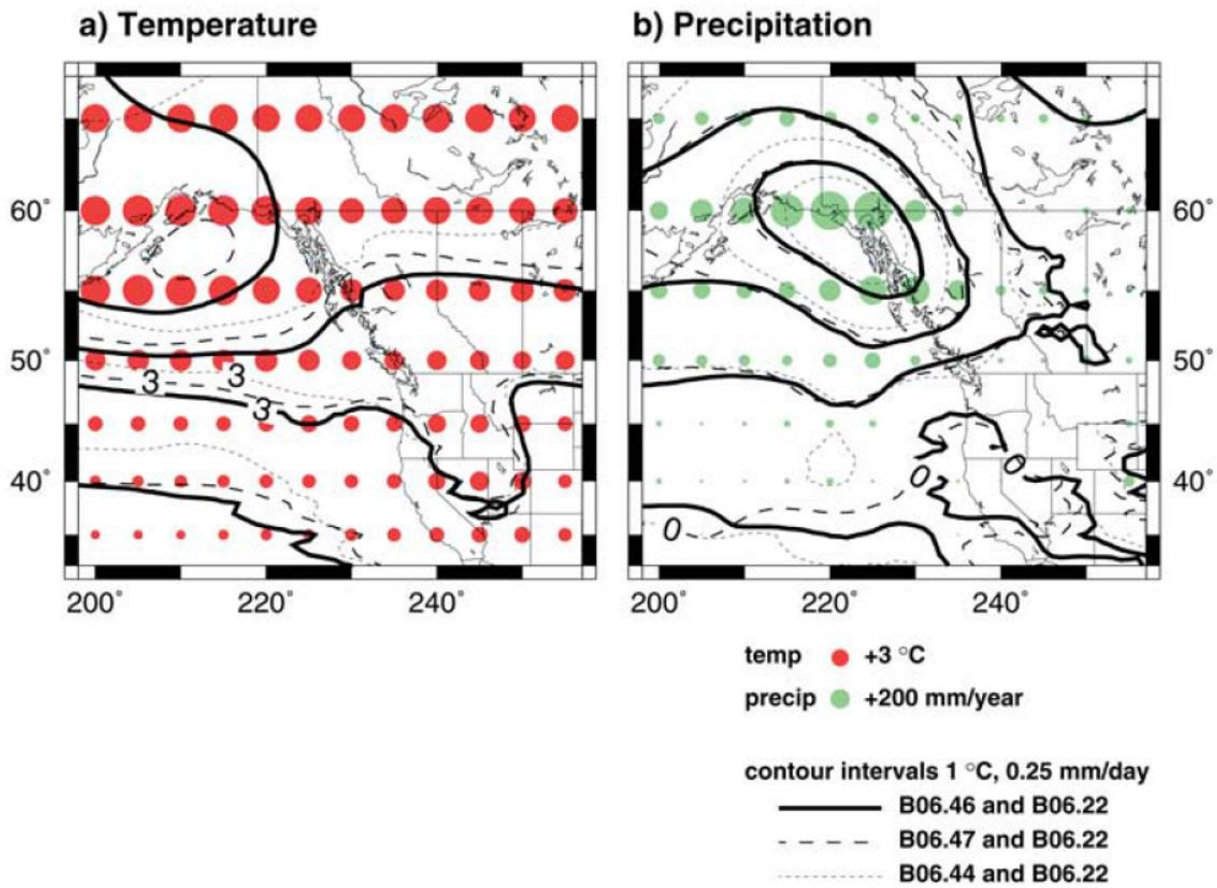

Figure 3.3. (a) Change in annual surface air temperature (°C, red dots) and (b) total precipitation (mm, green dots) for 2070 to 2099 relative to 1951 to 1980. Contours show temperature and precipitation changes for three different future climate model ensembles. The Alaska Region is located in the upper left portion of both figures (Stewart et al., 2004; Stewart et al., 2005).

Timlin and Walsh (2007) studied changes in arctic temperature and pressure by looking at seasonal frequency distributions of global climate model forecasts of maximum, minimum, and average daily temperatures. In comparing future years 2070 to 2089 with 1980 to 1999, they found that the overall increase in projected arctic temperatures is not evenly distributed throughout the seasons. **Figure 3.4** shows that December is projected to warm more significantly than the other seasonally representative months. The researchers also concluded that extreme low temperatures are projected to decrease in frequency while extreme high

temperatures are projected to increase in frequency in the Arctic. They did not report the statistical significance of their findings.

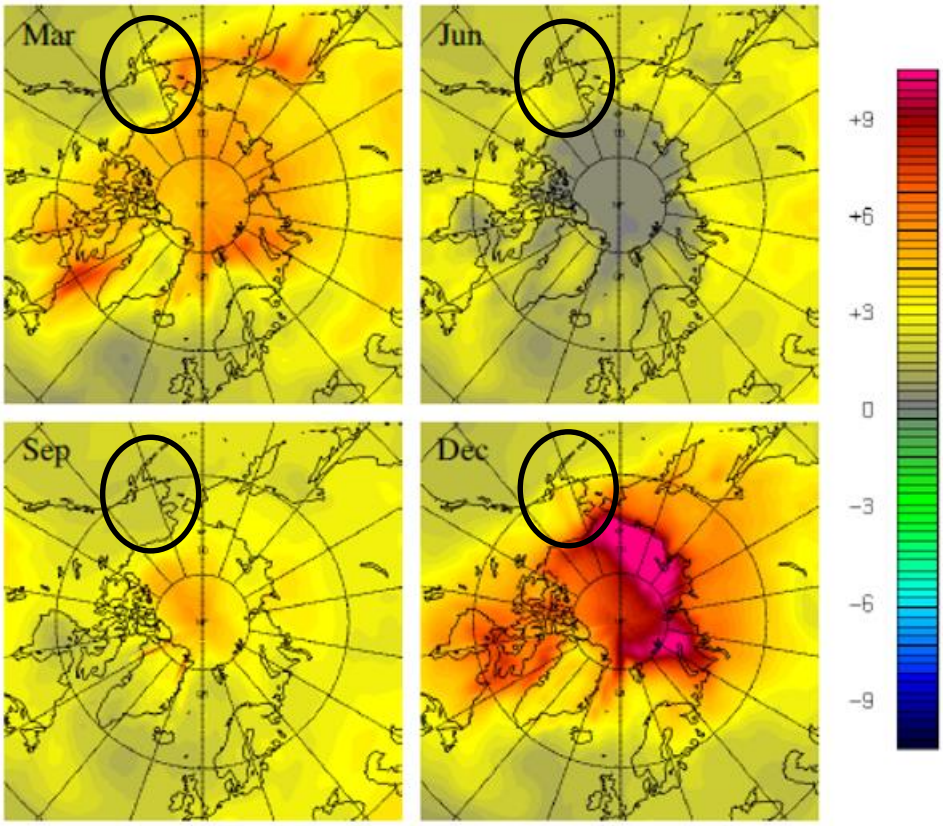

Figure 3.4. Five-model composite view of change in arctic mean surface air temperature from 1980-1999 to 2070-2089, for March, June, September, and December, in °C. The Alaska Region is within the black oval (Timlin and Walsh, 2007).

Stewart et al. (2013) also reported an increasing temperature trend for Alaska in the late 21st century, finding that the warming will be more significant in 2070 to 2099 than the more near-term future. **Figure 3.5** shows the average results of two climate scenarios for three different future time periods, using 14 (B1) or 15 (A2) global climate projection models. The authors report that the warming will be more extreme in northern Alaska, more extreme later in the century, and more extreme for the high (A2) emissions scenario. In all cases (shown with hatching in the figure), more than 50 percent of the models used for the analysis showed a statistically significant change in temperature, and more than 97 percent agree on the direction of the change.

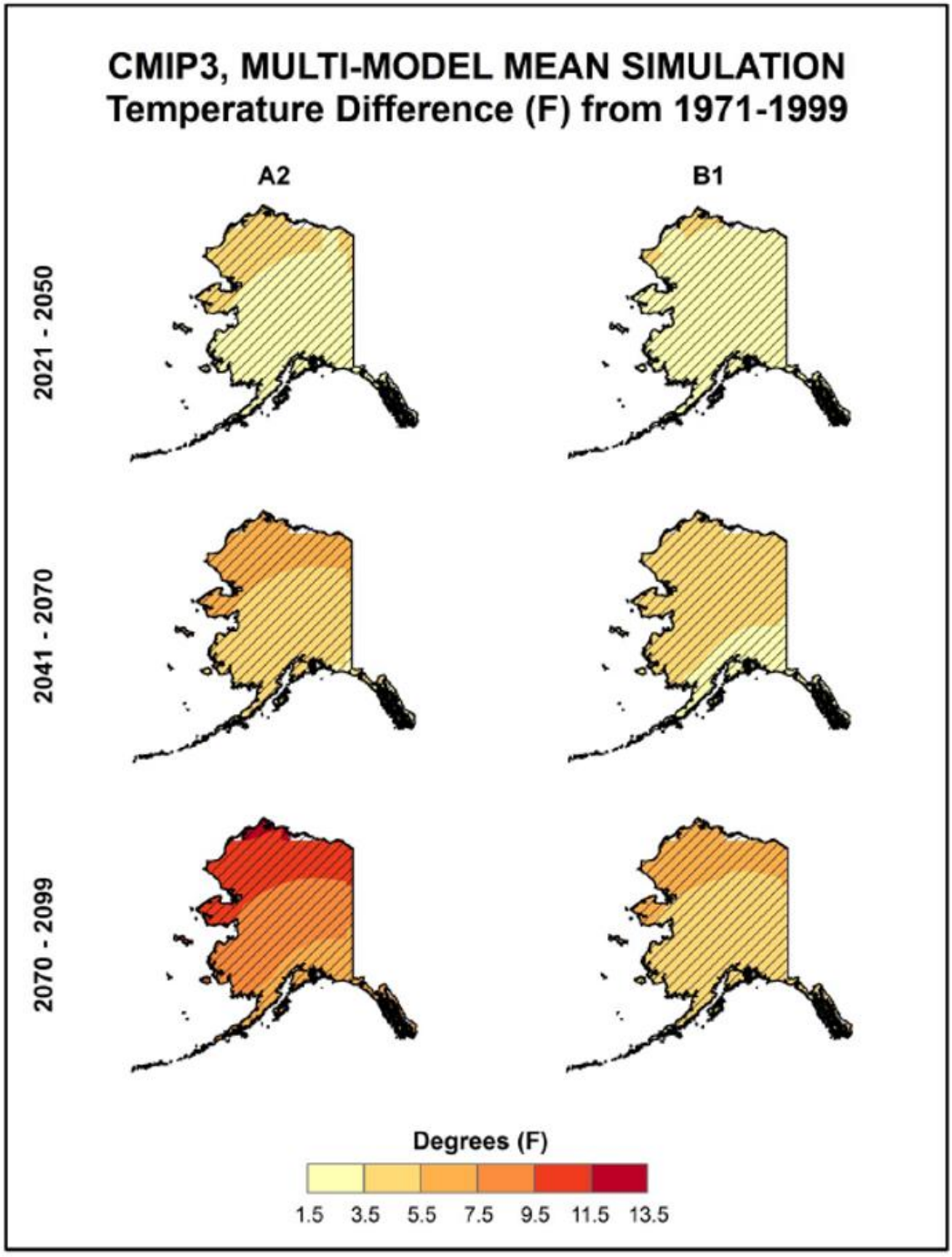

Figure 3.5. Simulated difference in annual mean temperature (°F) for Alaska for three future time periods with respect to the reference period of 1971 to 1999. Legend intervals in °F convert to 0.83, 1.9, 3.1, 4.2, 5.3, 6.4, and 7.5 °C (Stewart et al., 2013).

Stewart et al. (2013) also simulated mean seasonal temperatures for three future time periods: 2021-2050, 2041-2070, and 2070-2099 and determined that the warming will be greatest in the winter, followed by fall, spring, and summer, in that order. **Figure 3.6** shows the model results for the high emissions scenario.

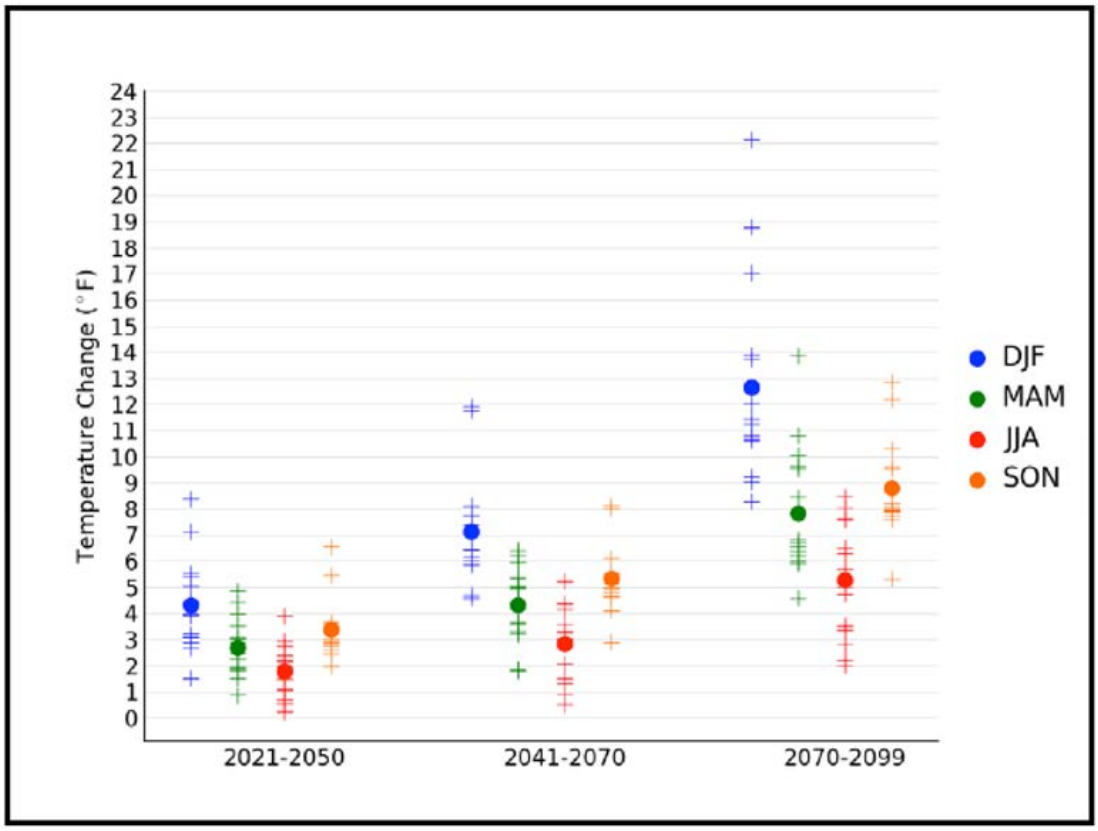

Figure 3.6. Simulated seasonal mean temperature change (°F) for Alaska, for three future time periods with respect to the reference period 1971-1999. Values are given for all 15 models for the high (A2) emissions scenario. The small plus signs indicate each individual model and the circles depict the multi-model means. Seasons are as follows: winter (December to February), spring (March to May), summer (June to August), and fall (September to November) (Stewart et al., 2013).

Key point: Recent climate projection studies concur that warming is predicted for the Alaska Region. Regional studies focused on Alaska and broader studies focused on the U.S. and Arctic show warming in the next century. As with past trends, warming is projected to be most significant in the winter. Cold extremes are projected to become milder (warmer), while extreme heat events are projected to become more frequent.

3.2. Precipitation

The third NCA reports the results of studies that conclude that annual precipitation totals are projected to increase in the future (Walsh et al., 2014). **Figure 3.7** shows a global map of projected percent change in annual precipitation totals under two emissions scenarios: rapid reductions from current emission rates and continued increases beyond current emissions rates. With continued emissions increases, the Alaska Region could see more than a 30 percent increase in annual precipitation.

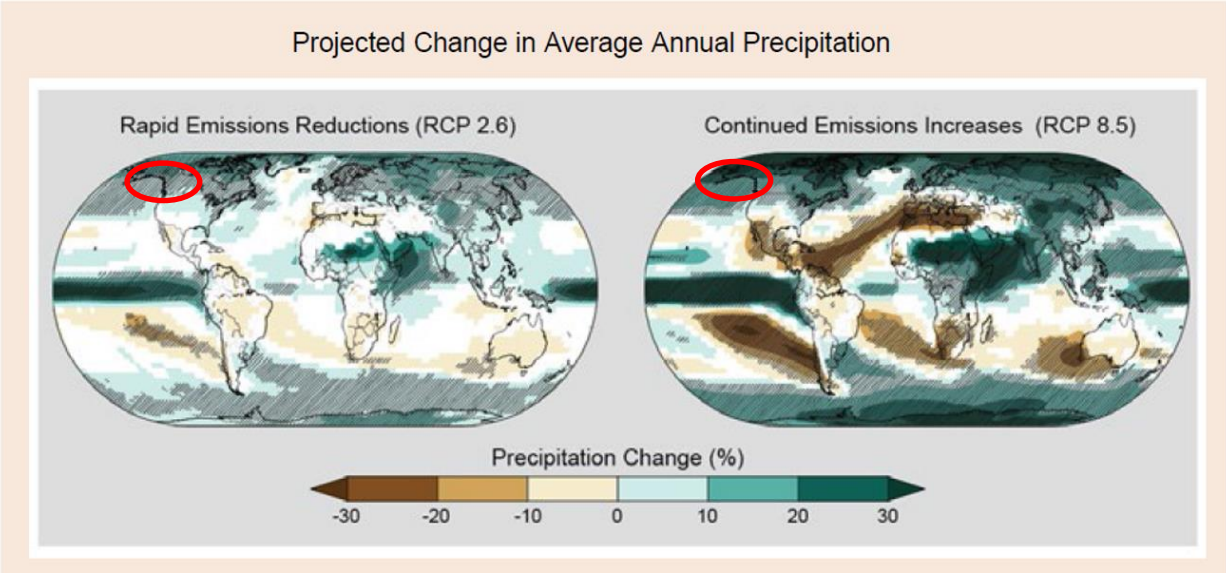

Figure 3.7. Projected change in average annual precipitation over the period 2071 to 2099, compared to the period 1970 to 1999. Hatched areas indicate confidence that the projected changes are significant and consistent among models. The Alaska Region is shown within the red oval (Walsh et al., 2014).

The precipitation increases may not be consistent throughout the seasons. Walsh et al. (2014) report the results of seasonal temperature projections under the same two emissions scenarios described above. **Figure 3.8** shows that under both scenarios, increases are projected across all seasons, with the highest increase projected for winter and the lowest projected for summer.

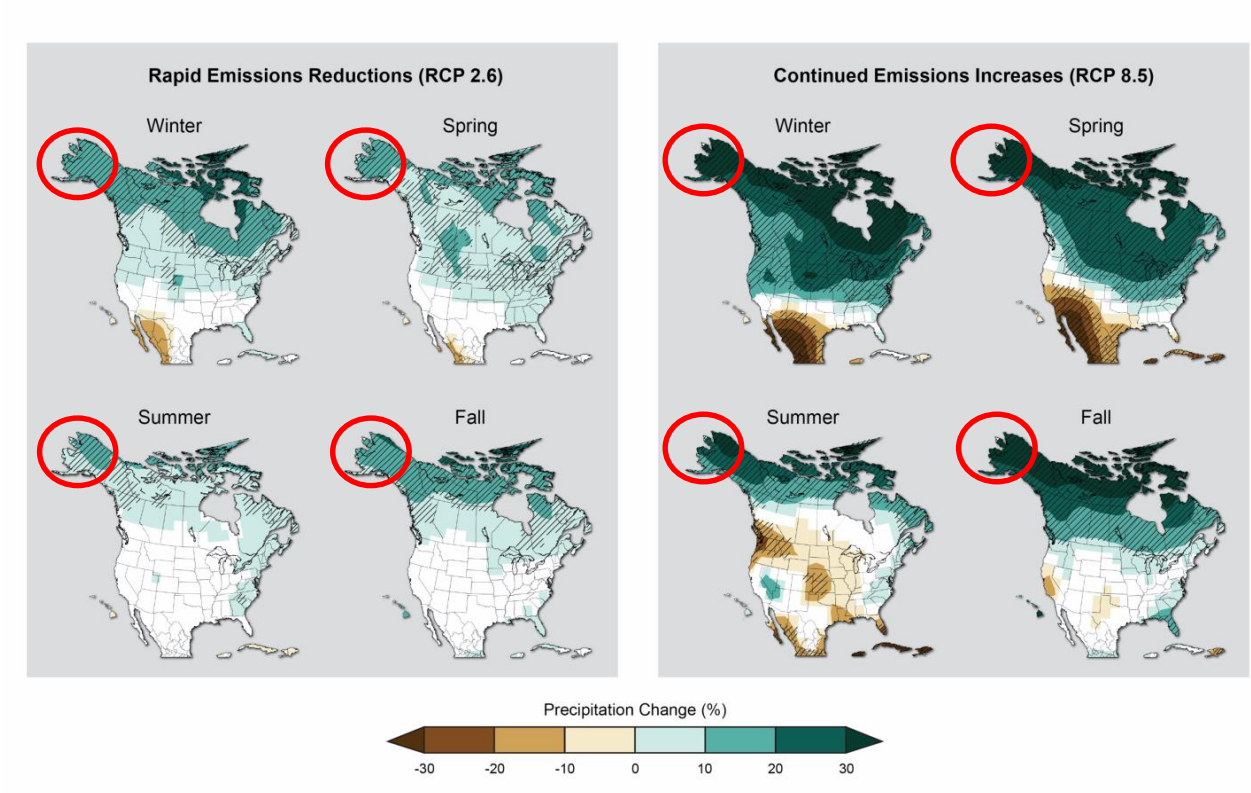

Figure 3.8. Seasonal precipitation change for 2071 to 2099, compared to 1970 to 1999 as projected by recent simulations. Hatched areas indicate that the projected changes are significant and consistent among models. The Alaska Region is shown within the red ovals (Walsh et al., 2014).

The authors also present climate projections that show changes in extreme precipitation statistics and events. Using the same two emissions scenarios described above for annual and seasonal changes, the annual maximum precipitation (the average of the wettest day of the year) in Alaska is projected to increase from 10 to over 40 percent. Continuing the trend of more precipitation, the number of consecutive dry days in Alaska is projected to decrease by up to 30 percent. **Figure 3.9** shows these findings and indicates where the climate models provide consistent projections.

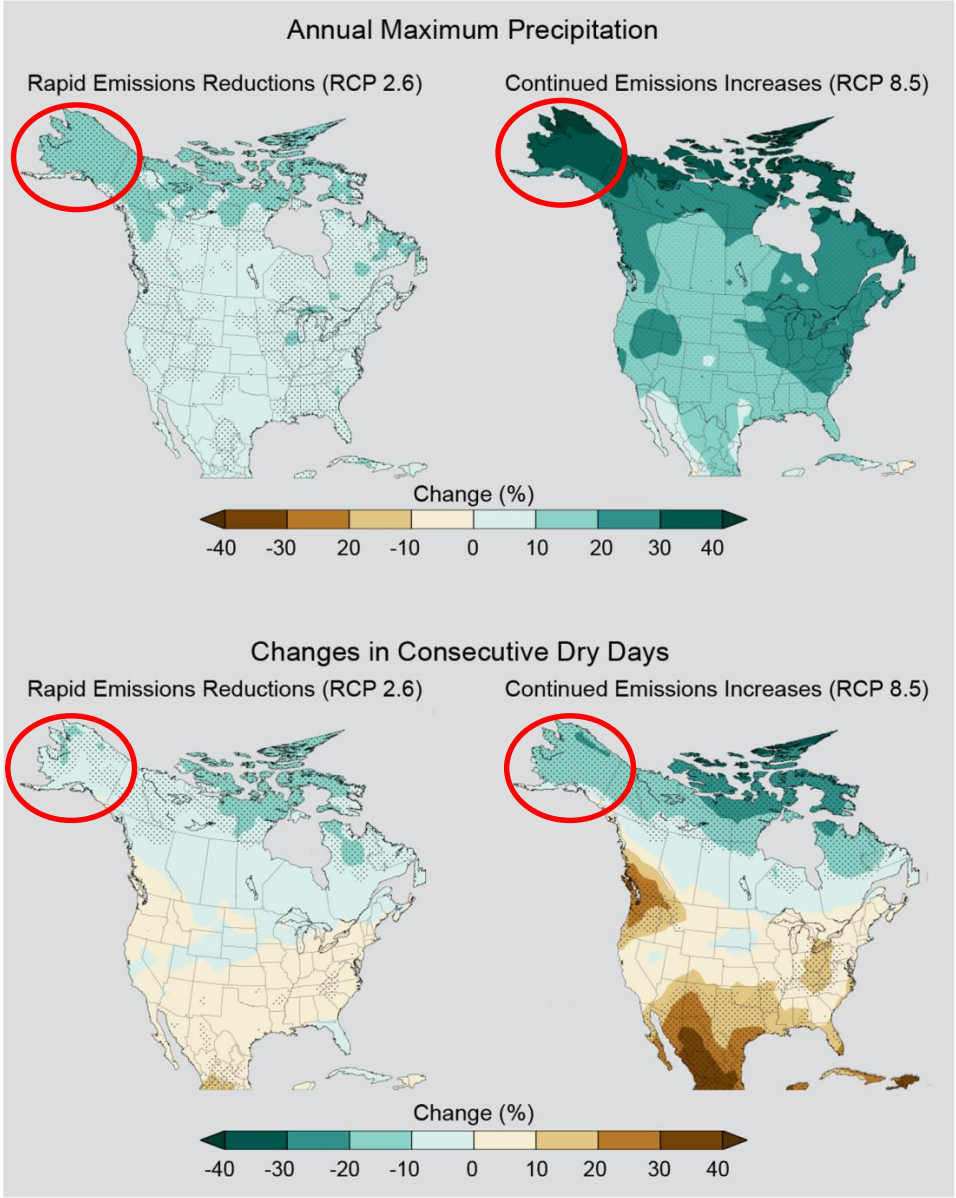

Figure 3.9. Top panels show simulated changes in the average amount of precipitation falling on the wettest day of the year for the period 2070 to 2099 as compared to 1971 to 2000 under two emissions scenarios. Bottom panels show simulated changes in the annual maximum number of consecutive dry days (days receiving less than 0.04 inches (1 mm) of precipitation) under the same two scenarios. Stippling indicates areas where changes are consistent among at least 80 percent of the models used in this analysis. The Alaska Region is shown within the red oval (Walsh et al., 2014).

Walsh et al. (2014) also reported on the projected change in heavy precipitation events, under the same two emissions scenarios. Consistent with the other projections for increased precipitation, the frequency of a 24-hour storm that now occurs once every 20 years would increase substantially for Alaska. This storm type is projected to occur 2 to 3 times more often for the emissions reduction scenario and 4 to 7 times more often for the emission increase scenario (**Figure 3.10**).

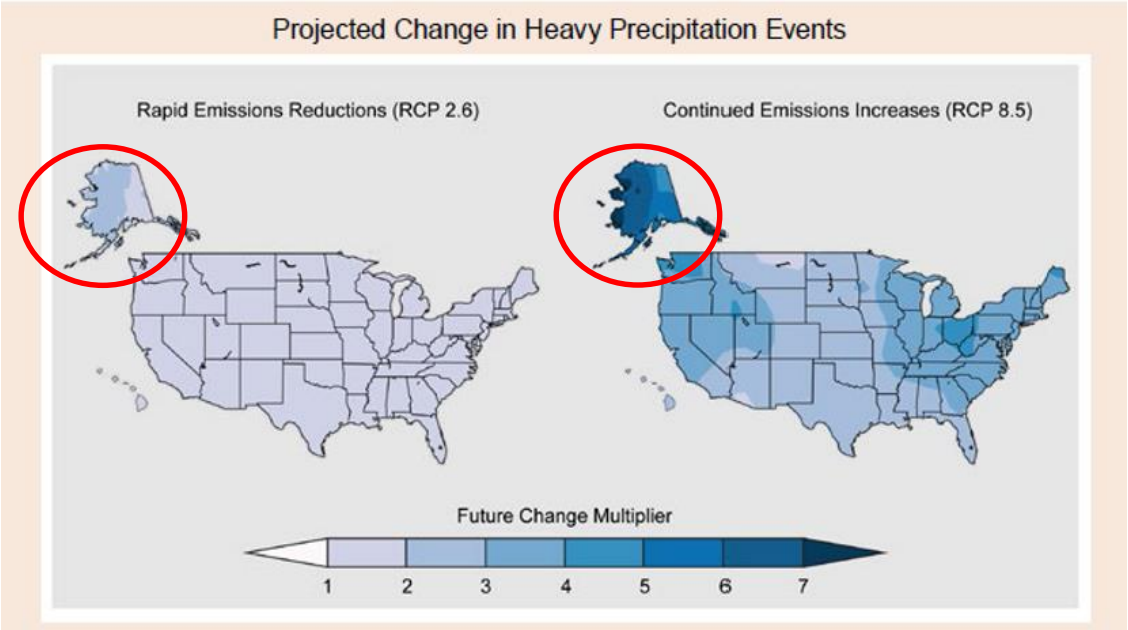

Figure 3.10. Maps show the increase in frequency of extreme daily precipitation events by the later part of this century (2081 to 2100) compared to the latter part of last century (1981 to 2000). The Alaska Region is shown within the red ovals (Walsh et al., 2014).

Other recent publications report projections consistent with the third NCA: that precipitation will increase in Alaska. Stewart et al. (2004) and Stewart et al. (2005) present the results of three different climate models projecting annual total precipitation increases of approximately 0.5 mm/day in Alaska (**Figure 3.3**).

Stewart et al. (2013) presented climate model results showing the different projected precipitation changes for different future time periods and for different seasons. In comparison to a 1971 to 1999 baseline average, the Alaskan precipitation, using a high emissions increase scenario, is projected to increase 5 to 10 percent by 2050. The change increases from 15 to 25 percent by 2070 and from 15 to 35 percent by 2099 (**Figure 3.11**). The projections are less for the low emissions increase scenario, resulting in 10 to 20 percent increase in precipitation by 2099. Deb et al. (2015) found similar annual precipitation increases (17 to 23 percent for three different scenarios) in a study focusing on future hydrologic changes in the Cook Inlet watershed (located in south-central Alaska) for 2040 to 2070.

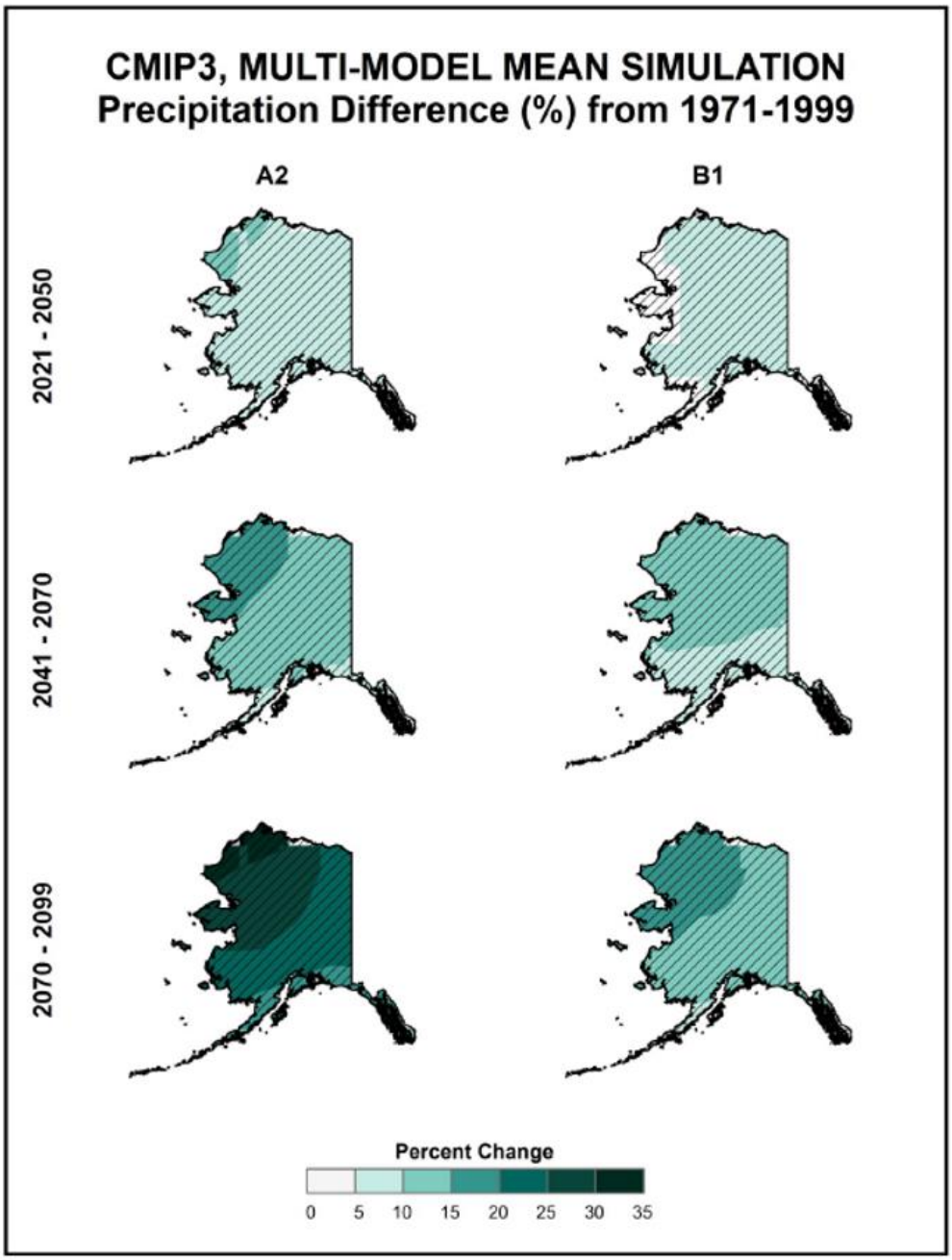

Figure 3.11. Simulated difference in annual mean precipitation (percent) for Alaska, for three future time periods with respect to the reference period of 1971 to 1999. A2 is a high emissions scenario and B1 is a low emissions scenario. Hatching indicates that more than 50 percent of the models used in this analysis showed a statistically significant change in precipitation, and more than 97 percent agree on the direction of the change (Stewart et al., 2013).

These increases are not projected to be constant through the seasons. **Figure 3.12** shows the model results presented by Stewart et al. (2013) for each season. These results show high inter-model variability, but that on average, winter precipitation will increase more than the other seasons.

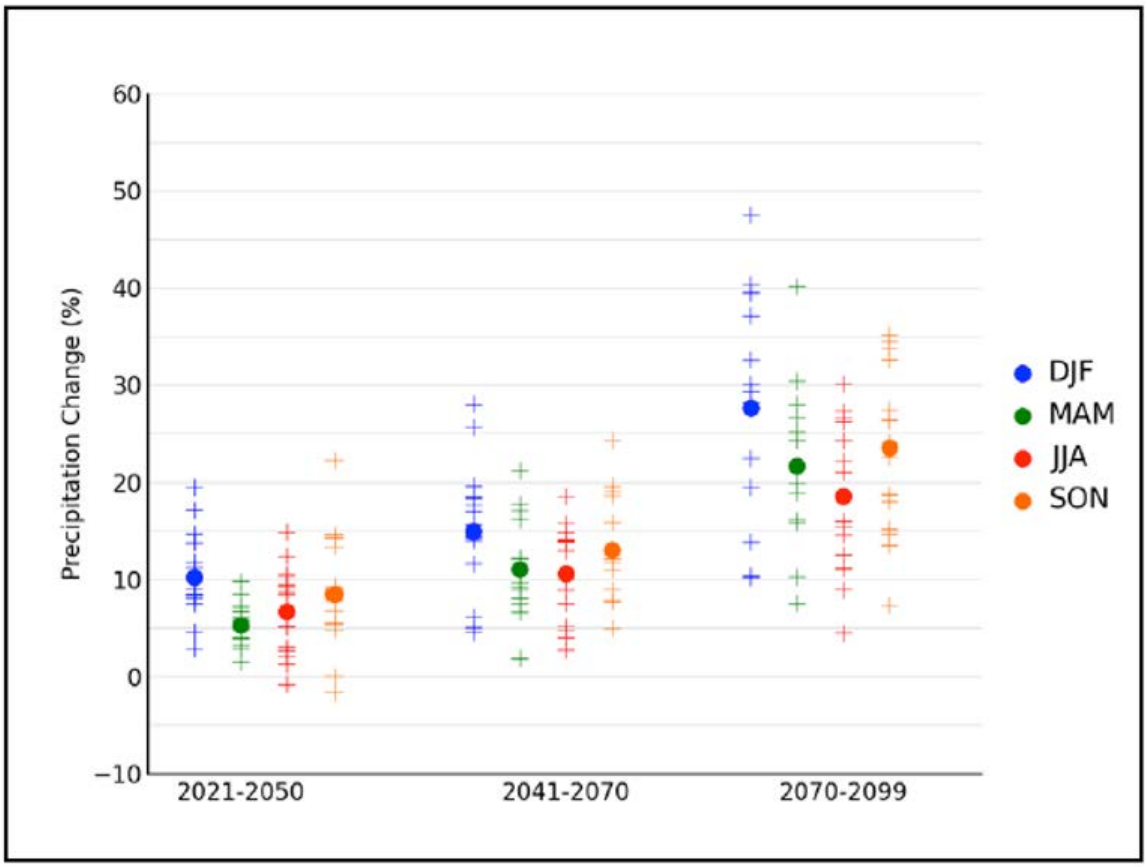

Figure 3.12. Simulated annual mean precipitation change (percent) for Alaska, for three future time periods with respect to the reference period of 1971 to 1999. Values are given for all 15 models for the high (A2) emissions scenario. The small plus signs indicate each individual model and the circles depict the multi-model means. Seasons are as follows: winter (December to February), spring (March to May), summer (June to August), and fall (September to November) (Stewart et al., 2013).

Key point: A consensus amongst recent peer-reviewed literature indicates an increase in projected annual precipitation, recurrence of large precipitation events, and a decrease in dry days in the Alaska Region.

3.3. Hydrology

The peer-reviewed literature evaluating projected changes to hydrology as a result of future climate change suggests that streamflow and runoff volume will increase and seasonal peak flow timing will be affected. Both global and regional studies were reviewed, presenting projections for hydrologic changes in Alaska.

Study projections from Hagemann et al. (2013), for the Alaska Region show an overall increase in runoff by up to 100 to 200 mm per year for their future planning horizon (2071-2100) compared to the recent historical baseline (1971-2000) (**Figure 3.13**), assuming an A2 emissions scenario. The increase is inconsistent across the seasons and throughout the region. The highest runoff increases along the southern coastline are expected to occur in fall and winter while the highest increases for the interior are expected in spring (**Figure 3.14**). The projected summer increases are small by comparison, with some decreases in runoff projected for coastal areas.

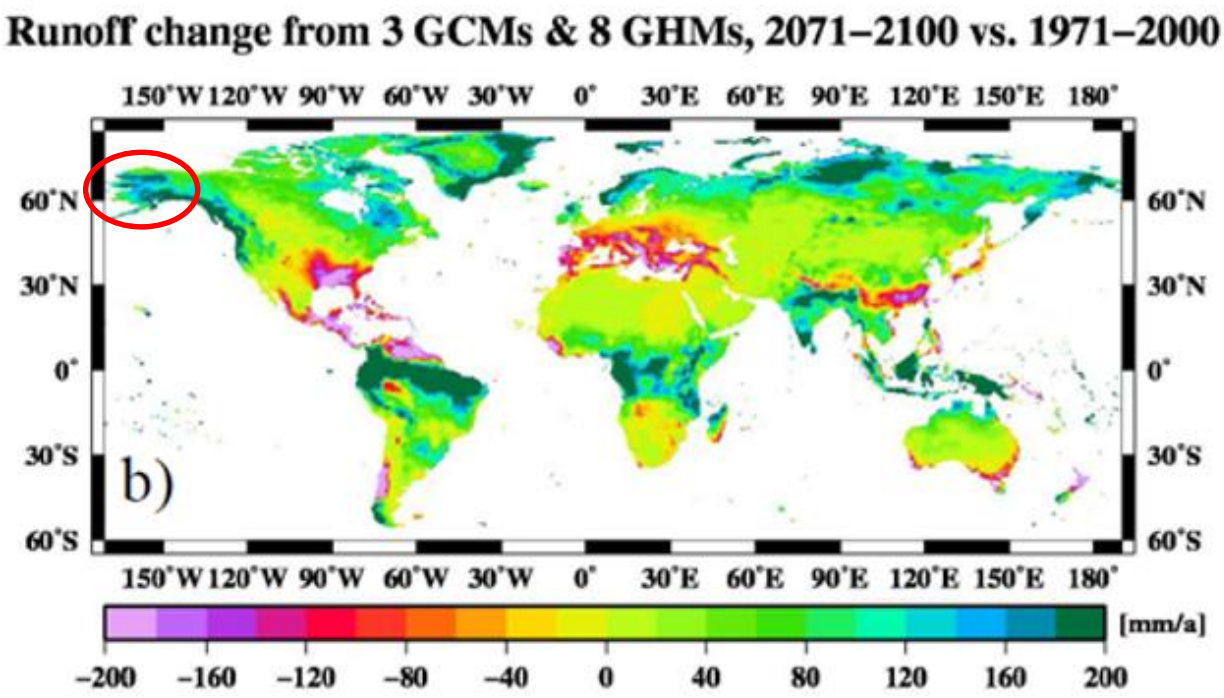

Figure 3.13. Ensemble mean runoff projections (mm/year) for A2 greenhouse gas emissions scenario, changes in annual runoff, 2085 vs. 1985. The Alaska Region is within the red oval (Hagemann et al., 2013).

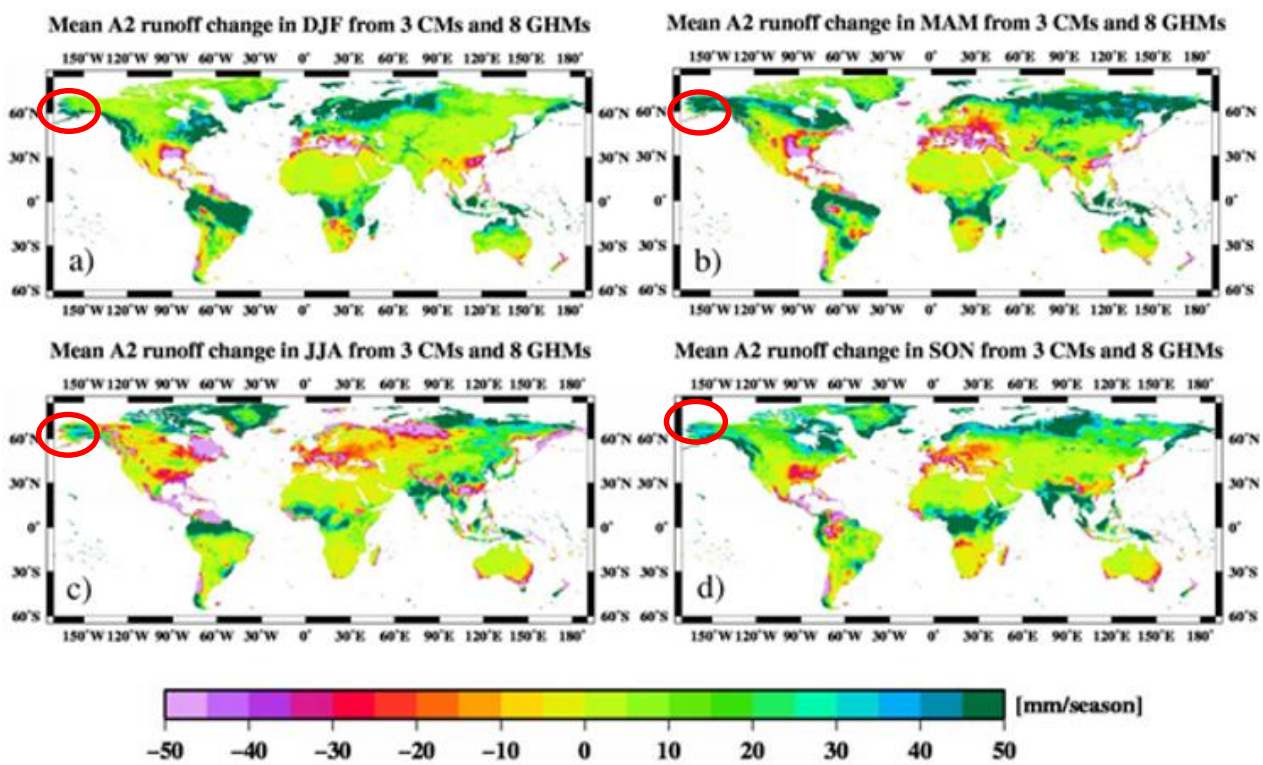

Figure 3.14. Ensemble seasonal (a. winter, b. spring, c. summer, d. fall) mean runoff projections (mm/season) for A2 greenhouse gas emissions scenario, changes in seasonal runoff, 2071-2100 vs 1971-2000. The Alaska region is within the red oval (Hagemann et al., 2013).

Döll and Zhang (2010) also evaluated projected changes in streamflow due to climate change on a global scale. The purpose of their study was to compare potential climate change impacts to the impacts of dams and other anthropogenic changes to freshwater ecosystems. Their findings suggest that streamflow will increase in the Alaskan Region, reporting a 10 to 80 percent increase in both the 90th percentile monthly low flow statistic and the average annual streamflow (**Figure 3.15** and **Figure 3.16**) in the later part of this century as compared to the later part of last century.

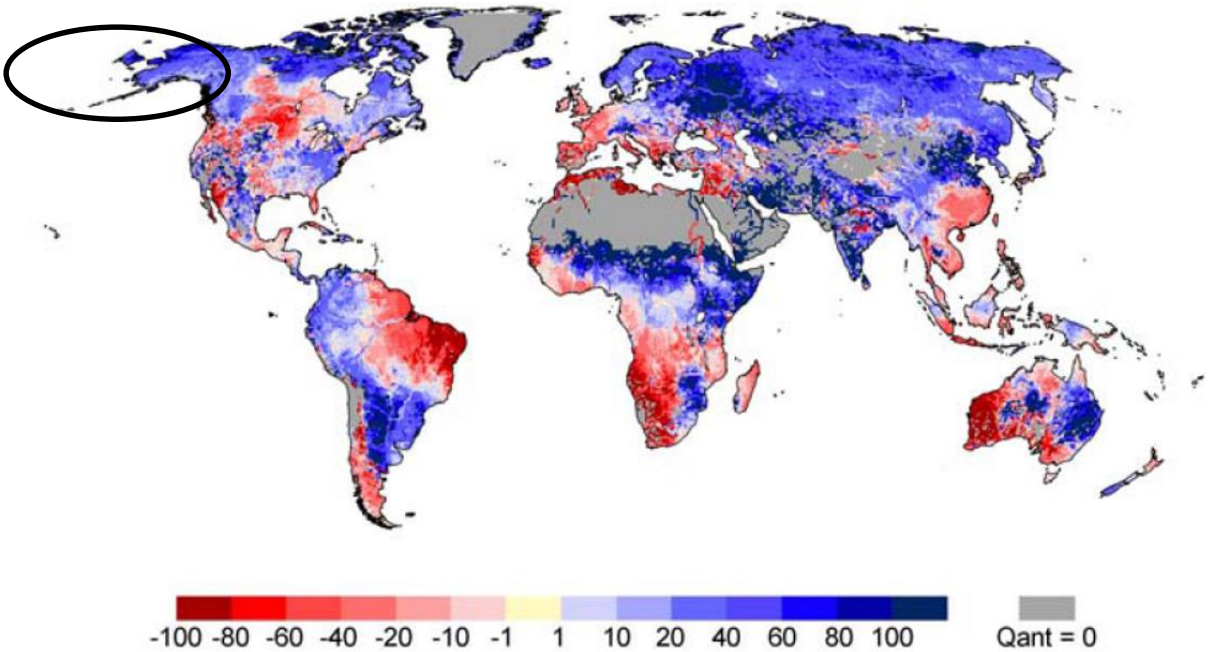

Figure 3.15. Percent difference in monthly low flow statistic (Q90) between 1961 to 1990 and 2041 to 2070 for the ECHAM4 B2 scenario. Two models and two scenarios evaluated showed similar results. The Alaska Region is within the black oval (Döll and Zhang, 2010).

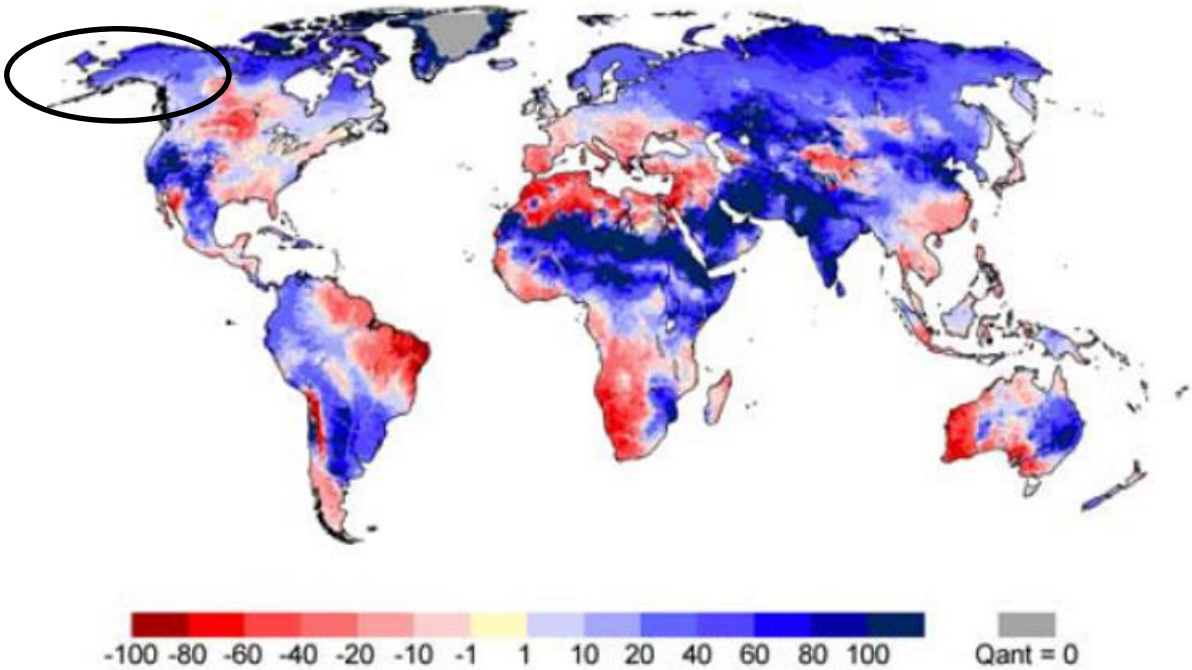

Figure 3.16. Percent difference in average annual flow from 1961 to 1990 and 2041 to 2070. The Alaska Region is within the black oval (Döll and Zhang, 2010).

Hay and McCabe (2010) studied potential changes in YRB runoff due to climate change using a water balance model. Results from this study indicate an increase in annual runoff over the 21st century for the YRB with increases in precipitation having the greatest effect on increases in runoff. Future increases in temperature were found to alter the timing of snow accumulation and melt, which would impact the timing of seasonal peak flows and infiltration.

Clilverd et al. (2011) also studied the impacts of global climate model projected changes in precipitation and temperature on Alaskan hydrology, focusing on groundwater recharge in northwest Alaska. They report a projected change in both the onset of snow accumulation and the onset of snow melt, both resulting in a shorter annual time of snow cover. The accompanying increase in precipitation cancels out the shorter snow cover time and results in no significant projected change in total annual snowmelt volume. **Figure 3.17** shows the results for total runoff and root to deep zone recharge flux in the northern aquifers. Slight increases in both measures can be seen in the later part of this century, attributable to the overall increased precipitation.

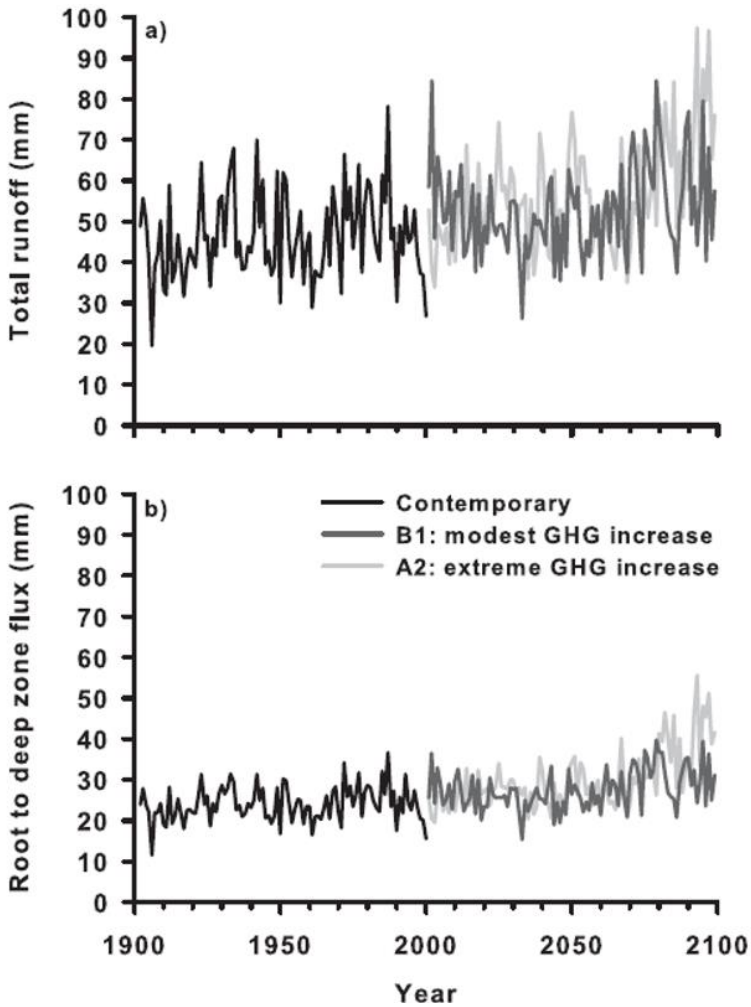

Figure 3.17. (a) Comparisons of annual total runoff and (b) annual root to deep soil zone flux (aquifer recharge) (Clilverd et al., 2011).

Stewart et al. (2004) and Stewart et al. (2005) also studied the timing of runoff as a result of future changes in temperature and precipitation in portions of Alaska. The authors concluded that the centroid of annual streamflow will continue to move earlier and earlier in the year through the remainder of this century (**Figure 3.18**). The centroid of annual streamflow is an indicator of the timing of peak runoff season, which, in Alaska, is driven by snowmelt runoff.

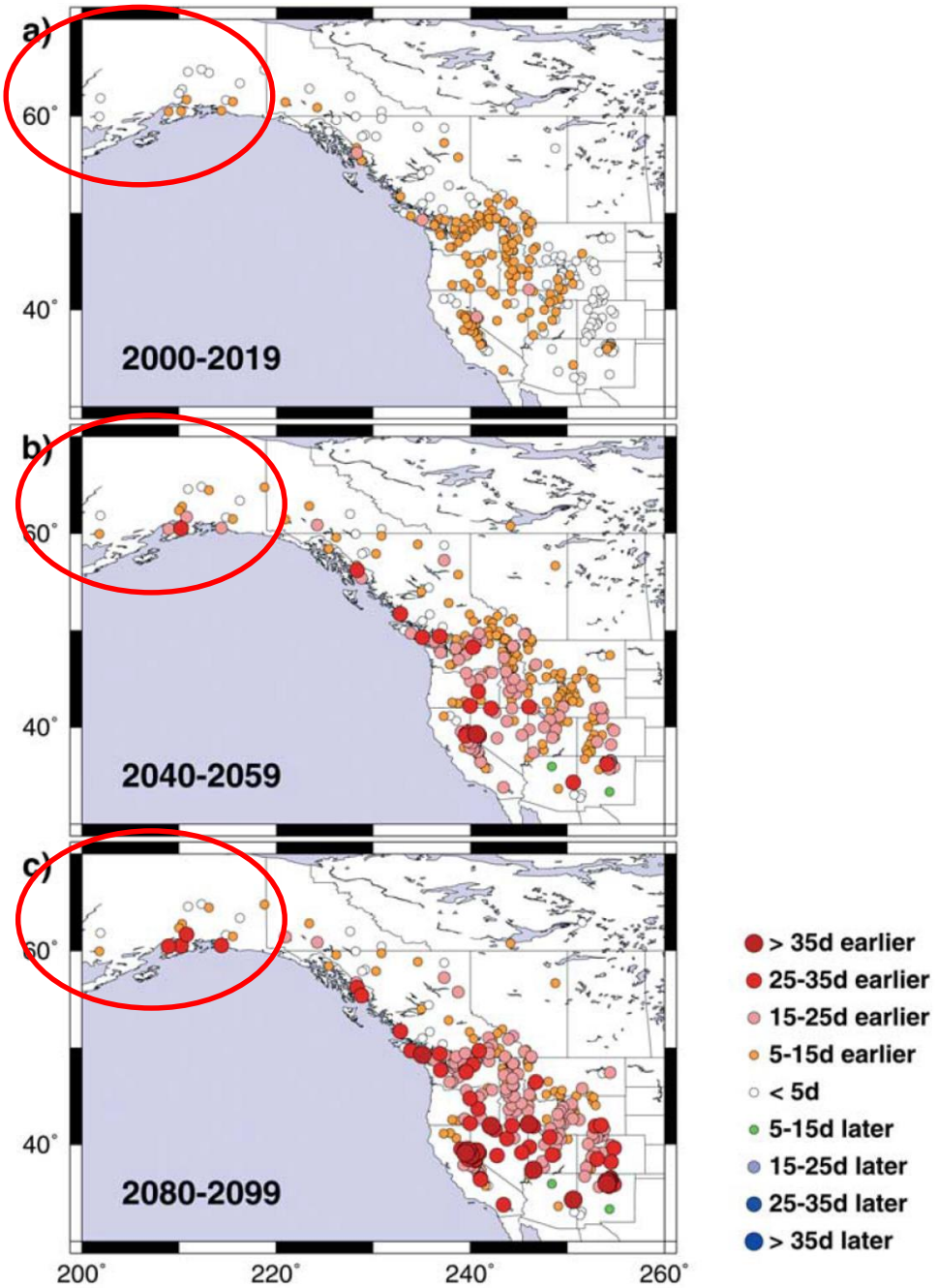

Figure 3.18. The 20-year averages of projected changes in the centroid of annual flow (CT), compared to a 1951 to 1980 baseline. A portion of the Alaska Region was included in the study and is shown in the red oval (Stewart et al., 2004; Stewart et al., 2005).

Most recently, Deb et al. (2015) studied hydrologic changes due to projected climate change in the Cook Inlet watershed for 2040 to 2070. The Cook Inlet watershed covers 47,000 square miles of south-central Alaska. The authors found that future precipitation and temperature increases will lead to streamflow increases, including an increase in the 7-day low flows and a considerable increase in the 100-year peak flow. Deb et al. (2015) also agrees with previous research that the centroid of annual flow will occur earlier due to earlier snowmelt patterns. **Figure 3.19** shows their results for projected seasonal change in water yield, evapotranspiration, runoff, and groundwater recharge. Strong seasonal patterns are evident in the projected changes for these various hydrologic metrics. The increase in water yield is projected to be near or above 30 percent for all seasons except summer, which is projected to increase 5 to 15 percent. The increase in evapotranspiration is greatest in winter, with a 20 to 40 percent projected increase compared to near or less than 10 percent increase for the other seasons. Winter is projected to have a very large increase in runoff compared to the other seasons. This finding is somewhat contradictory to Hagemann et al. (2013), who predicted larger runoff increases in the spring (both studies defined the seasons as noted in **Figure 3.14**). The projected change in recharge is most well distributed through the seasons with fall and winter increasing 20 to 30 percent and spring and summer increasing 30 to 40 percent.

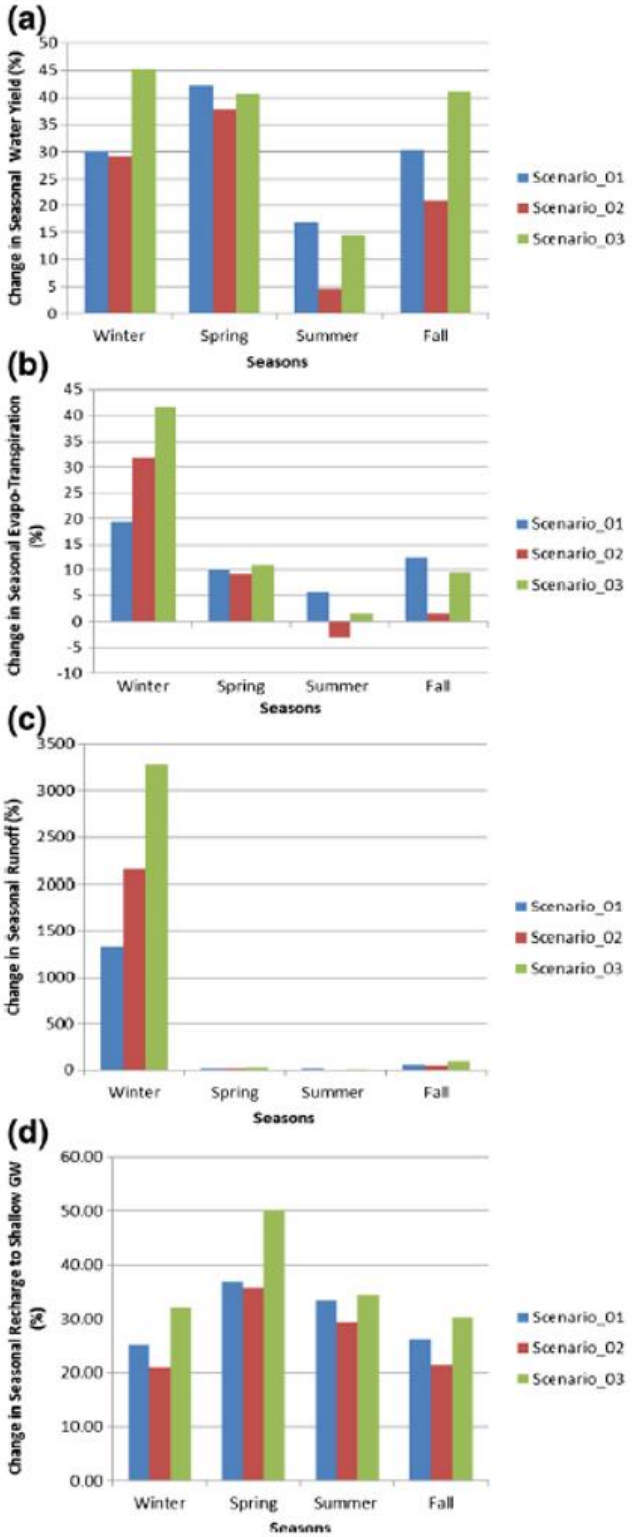

Figure 3.19. (a) Seasonal variation in projected water yield, (b) evapotranspiration, (c) runoff and (d) groundwater recharge for the Cook Inlet watershed in Alaska (Deb et al., 2015).

Key point: Increases in precipitation are expected to result in increases in runoff and streamflow. Increases in temperature are expected to result in a shorter annual time of snow cover and increased evapotranspiration. There is general consensus that the increased liquid precipitation will more than compensate for the reduction in snowmelt and increase in evapotranspiration.

3.4. Summary of Future Climate Projection Findings

There is a consensus in the scientific literature that air temperatures will trend upwards over the next century in the Alaska Region. A general consensus amongst recent peer-reviewed literature indicates an increase in projected annual precipitation, recurrence of large rain events, and dry days in the region. Studies also concur on a projected increase in runoff as a result of large increases in precipitation that overcome increases in temperature. Changes in snowmelt timing are projected to cause earlier seasonal peak flows.

The trends and literary consensus of observed and projected primary variables noted above have been summarized for reference and comparison in the following figure (**Figure 3.20**).

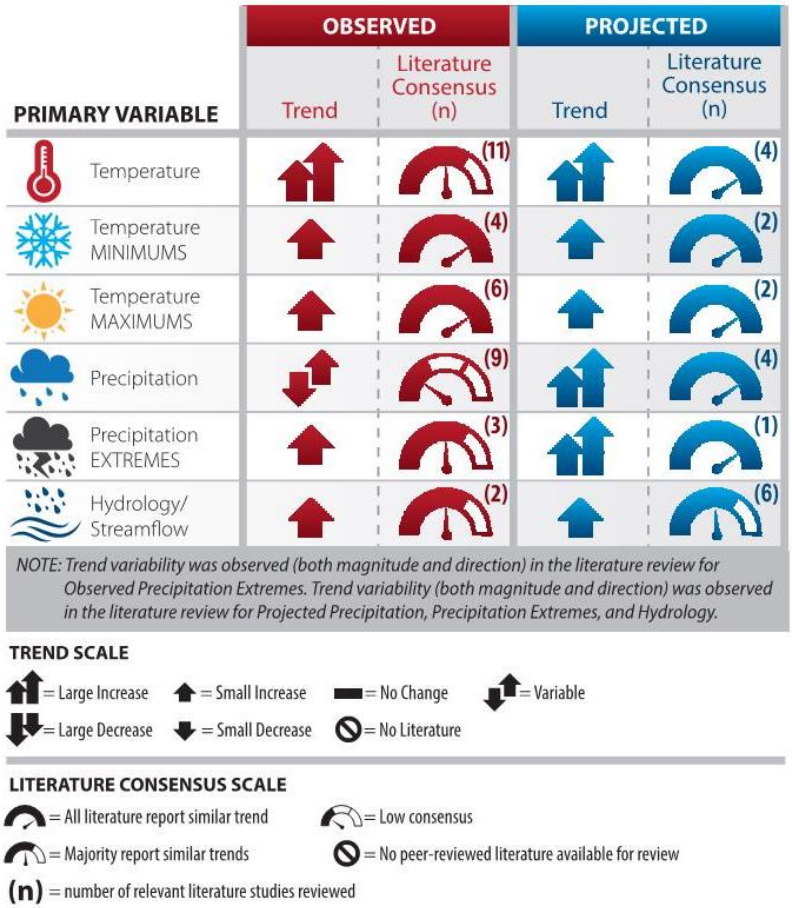

Figure 3.20. Summary matrix of observed and projected climate trends and literary consensus.

4. Business Line Vulnerabilities

The Alaska Region encompasses the state of Alaska and the edges of the Canadian border. Impacts to this area will be affected by climatic conditions beyond this given region, including from Canada. USACE recognizes the potential impacts of future climate considering the exposure and dependency of many of its projects on the natural environment. To assess the potential vulnerabilities that climate change may pose on USACE's missions, a set of primary USACE business lines were identified. They include:

- Navigation
- Flood Risk Management
- Ecosystem Restoration
- Recreation
- Emergency Management
- Regulatory
- Military Programs

The USACE navigation mission in the Alaska Region is to be responsible for channel maintenance, hydrographic surveys, and ports and harbors. By the end of the century, the Alaska Region may experience increases in ambient air temperature and an increase in streamflow. This has implications for water levels and thus the ability for vessels to navigate and dock in ports, and may impact the dredging activities at harbor entrances.

USACE implements flood risk management projects in the region, including structural projects to prevent erosion. It is predicted that the region will experience an increase in annual precipitation, streamflow, and runoff. This may increase flooding risks. Flood risk management projects may be very important for reducing the residual flooding impacts.

While this report does not highlight the impacts of sea level change, changes in coastal conditions can have impacts which penetrate to inland water bodies. Rapidly melting Alaskan glaciers are contributing to global sea level rise (Stuart et al., 2014). Tools and information related to sea level change can be found on the USACE Responses to Climate Change website (USACE, 2014).

USACE implements several ecosystem restoration projects in the Alaska Region. Increased air temperatures will result in increased water temperatures. This may lead to water quality concerns, particularly for the dissolved oxygen levels, which are an important water quality parameter for aquatic life. Increased air temperatures influence wildlife and supporting food supplies. Streamflows and runoffs may also increase, which may cause flooding which in turn raises ecological concerns and may threaten ecosystems.

Recreational facilities in the Alaska Region offer several benefits to visitors as well as positive economic impacts. Increases in air temperature may impact the number of visitors to USACE's recreational facilities.

USACE has extraordinary capabilities to respond to natural disasters and other emergency situations throughout the country, and it is a top priority. There are designated emergency managers and assigned staff in each region and subregion that are able to quickly mobilize.

Large precipitation events are capable of creating emergency situations in which USACE would be needed to provide assistance in the Alaska Region. Since precipitation is expected to fall in larger events, these disaster situations may occur more frequently, USACE can expect an increased need for their assistance in disaster response and recovery.

USACE's regulatory mission has a serious commitment to protecting aquatic resources while allowing for reasonable development. The climate projections may have indirect implications for permitting in the region, and may result from modifications in federal laws and guidance. This may spur stricter regulations or an increase in the permitting breadth and depth. While most of the permitting processes may not change, the volume and frequency of the permitting requirements may increase – thus increasing the permitting costs for projects.

In addition, USACE provides engineering, construction, real estate, environmental management, disaster response, and other support or consulting services for the Army, Air Force, other assigned U.S. Government agencies, and foreign governments. Environmental management services including the rehabilitation of active and inactive military bases, formerly used defense sites, or areas that house excess munitions. Expected changes in climate may necessitate adjustments in rehabilitation approaches, engineering design parameters, and potential types of military construction/infrastructure projects that USACE may be asked to support.

USACE projects are varied, complex, and at times, encompass multiple business lines. The relationships among these business lines, with respect to impacts from climate change, are complicated with cascading effects. Such interrelationships must be recognized as an essential component of future planning efforts when considering the best methods or strategies to adapt. **Figure 4.1** summarizes the projected climate trends and impacts on each of the USACE business lines.

CLIMATE VARIABLE	VULNERABILITY
Increased Ambient Temperatures	Increased ambient air temperatures throughout the century, and over the next century are expected to create the following vulnerabilities on the business lines in the region: • Loss of vegetation due to a change in ecosystem, may have impacts within the region. It may impact sediment stabilization in the watershed. Loss of vegetation may result in an increase in sediment loading, potentially causing geomorphic changes in the tributaries to the river system. • Increased temperatures may have negative consequences for all infrastructure, habitats, and people in the area. **BUSINESS LINES IMPACTED:**
Increased Annual Precipitation	By the end of the century, annual precipitation is expected to increase in the region which are expected to influence the following vulnerabilities on business lines in the region: • Increased flows and runoff, which may carry pollutants to receiving water bodies, decreasing water quality. • Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns. • Increased flooding, which may have negative consequences for all infrastructure, habitats, and people in the area. **BUSINESS LINES IMPACTED:**
Streamflow Variability	Streamflow and runoff are expected to increase by the end of the century. This includes an increase in overall flow and an increase of peak flow: • Increased flows and runoff, which may carry pollutants to receiving water bodies, decreasing water quality. • Increased erosion with subsequent changes in sediment accumulation rates and creating water quality concerns. • Increased flooding, which may have negative consequences for all infrastructure, habitats, and people in the area. **BUSINESS LINES IMPACTED:**

NOTE: The Regulatory and Military Program business lines may be impacted by all climate variables

= Navigation = Flood Risk Management = Ecosystem Restoration = Hydropower = Recreation = Water Supply = Emergency Management

Figure 4.1. Summary of projected climate trends and impacts on USACE business lines

Appendix A: References Climate/Hydrology Summary Table

References	Observed										Projected									
	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification	Mean Temperature	Temperature Minimums	Temperature Maximums	Precipitation	Precipitation Extremes	Hydrology/Streamflow	Drought Indices	Soil Moisture	Spring Onset Index	Climate Classification
Arendt A, Walsh J, Harrison W (2009)	X			X																
Bieniek, PA., Wash, JE., Thoman, RL., Bhatt, US (2012)	X																			
Bieniek, P., U. Bhatt, R. Thoman, H. Angeloff, J. Partain, J. Papineau, F. Fritsch, E. Holloway, J. Walsh, …, R. Gens (2014).	X																			
Brabets TP, Walvoord MA (2009)						X														
Clilverd HM, White DM, Tidwell AC, Rawlins MA (2011)														X		X				
Deb D, Butcher J, Srinivasan R (2015)														X		X				
Döll P, Zhang J (2010)																X				
Hagemann S, Chen C, Clark DB, Folwell S, Gosling SN, Haddeland I, Hanasaki N, Heinke J, Ludwig F, Voss F, Wiltshire AJ (2013)																X				
Hay LE, McCabe GJ (2010)														X		X			X	
Hinzman LD, Bettez ND, Bolton WR, Chapin FS, Dyurgerov MB, fastie CH, Griffith B, Hollister RD, Hope A,…,Yoshikawa K (2005)	X			X																
Kunkel KE, Bromirski PD, Brooks HE, Cavazos T, Douglas AV, Easterling DR, Emanuel KA, ..., Smith RL (2008)	X	X		X	X															
Markon CJ, Trainor SF, Chapin FS (2012)	X	X	X	X	X															
McAfee, S. A., G. Guentchev, and J. K. Eischeid (2013)				X																
McAfee, S., G. Guentchev, and J. Eischeid (2014)				X																
Milly PC, Betancourt JL, Falkenmark M, Hirsch R, Kundzewicz Z, Lettenmaier D, Stouffer R (2008)											X									
Peterson TC, Villarini G, Heim RR, Hirsch R, Kaiser DP, Brooks H, Diffenbaugh NS, …,Woodhouse CA, Wuebbles D (2013)		X	X																	
Polyakov IV, Bekryaev RV, Alekseev GV, Bhatt US, Colony RL, Johnson MA, Askshtas APM, Walsh D (2002)	X																			
Stafford JM, Wendler G, Curtis J (2000)	X			X																
Stewart BC, Kunkel KE, Stevens LE, Sun L, Walsh JE (2013)	X			X	X						X	X	X	X						
Stewart IT, Cayan DR, Dettinger MD (2004)						X					X			X		X			X	
Timlin MS, Walsh JE (2007)											X	X	X							
Walsh J, Wuebble D, Hayhoe K, Kossin J, Kunkel K, Stephens G, Thorne P, Vose R, Wehner M, ..., Somerville R (2014)	X			X	X						X	X	X	X	X					
Wendler G, Chen L, Moore B (2012)	X																			
Wendler G, Shulski M (2009)	X	X	X	X					X											

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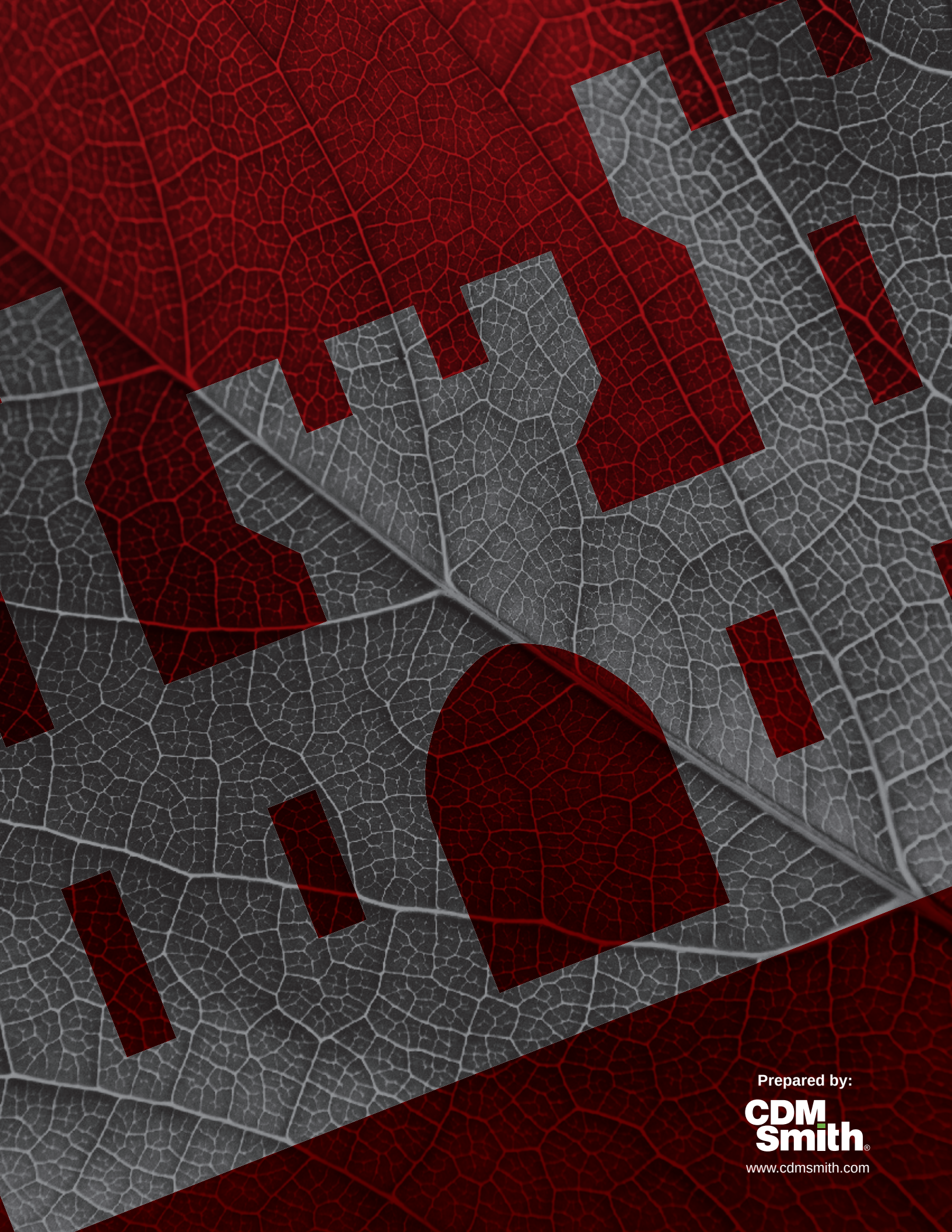

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